ICHEP 2024

Multi-differential charged-particle jet fragmentation in pp collisions with ALICE

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On behalf of the ALICE collaboration

Pusan National University

18 July 2024

ALICE

PUSAN NATIONAL UNIV.

NPL

NUCLEAR PHYSICS LAB

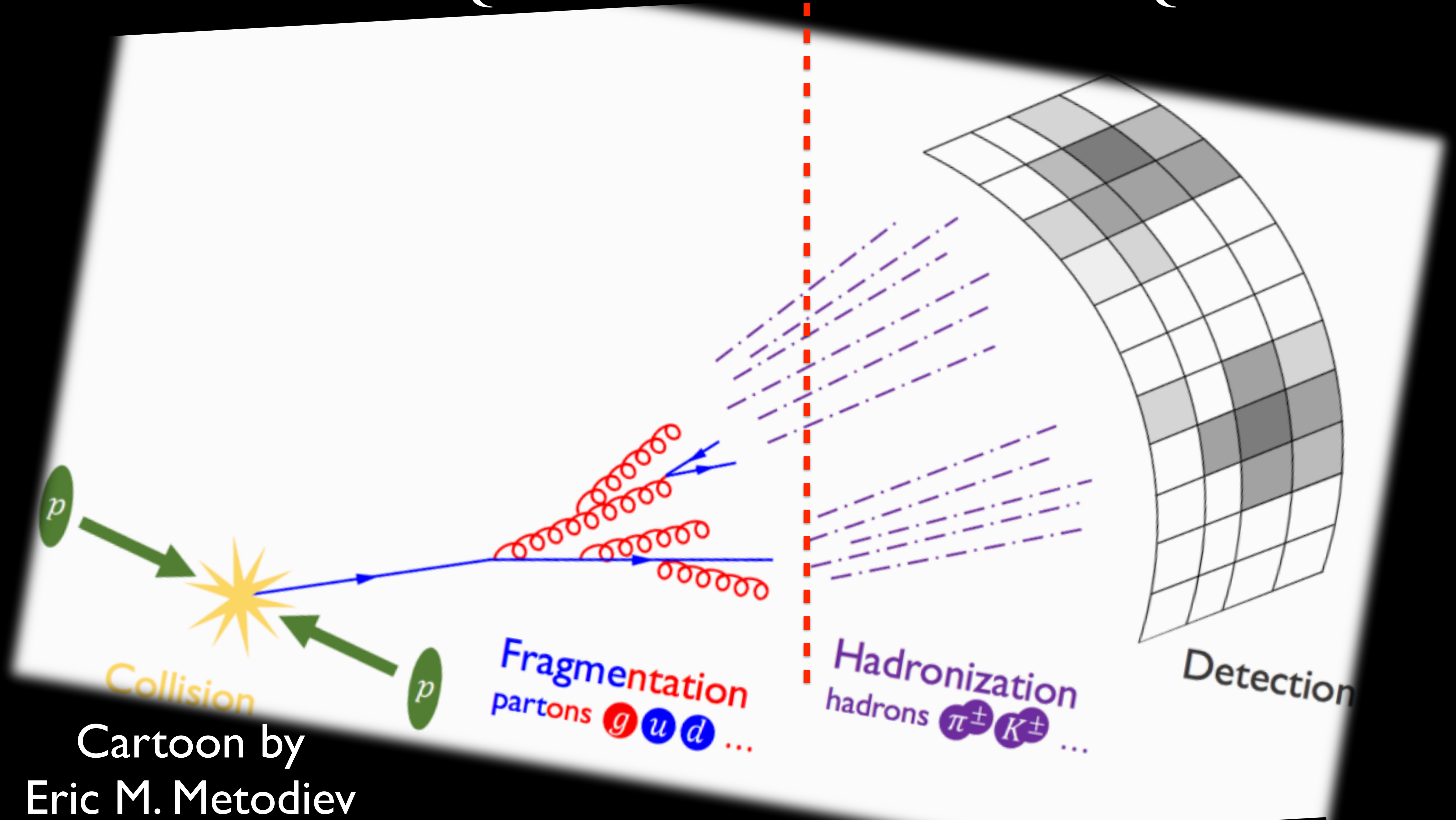
Study of jets substructure

What can we do with jets in such collision system ?

QCD in vacuum

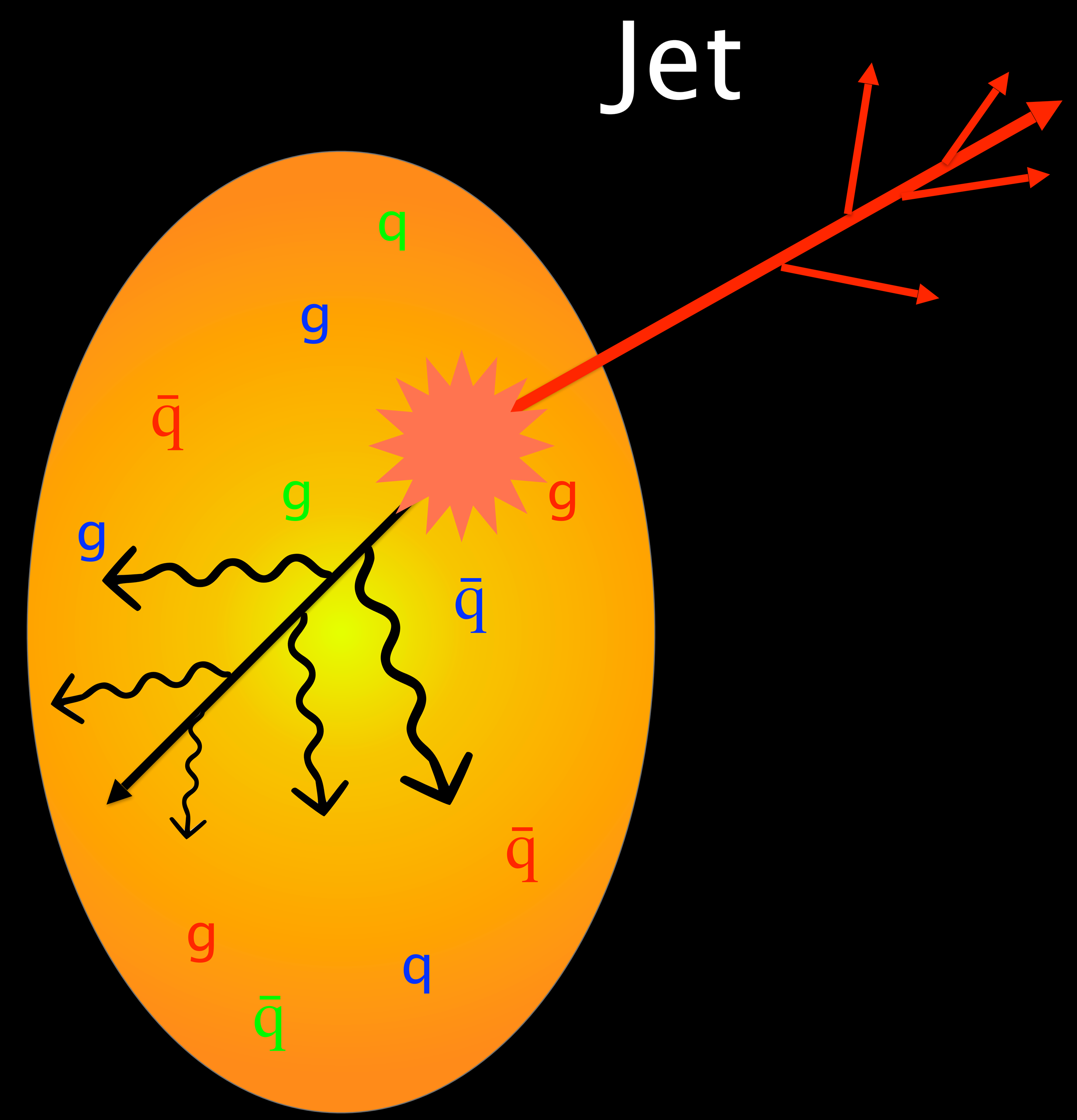
QCD jet evolution process

Parton showering	Hadronization
pQCD	non-pQCD
$Q^2 >> \lambda_{QCD}$	$Q^2 \approx \lambda_{QCD}$



Cartoon by
Eric M. Metodiev

Properties of QGP



Jet-medium interaction

Baseline measurement for QGP studies in pp

Study of jets substructure

What can we do with jets in such collision system ?

QCD in vacuum

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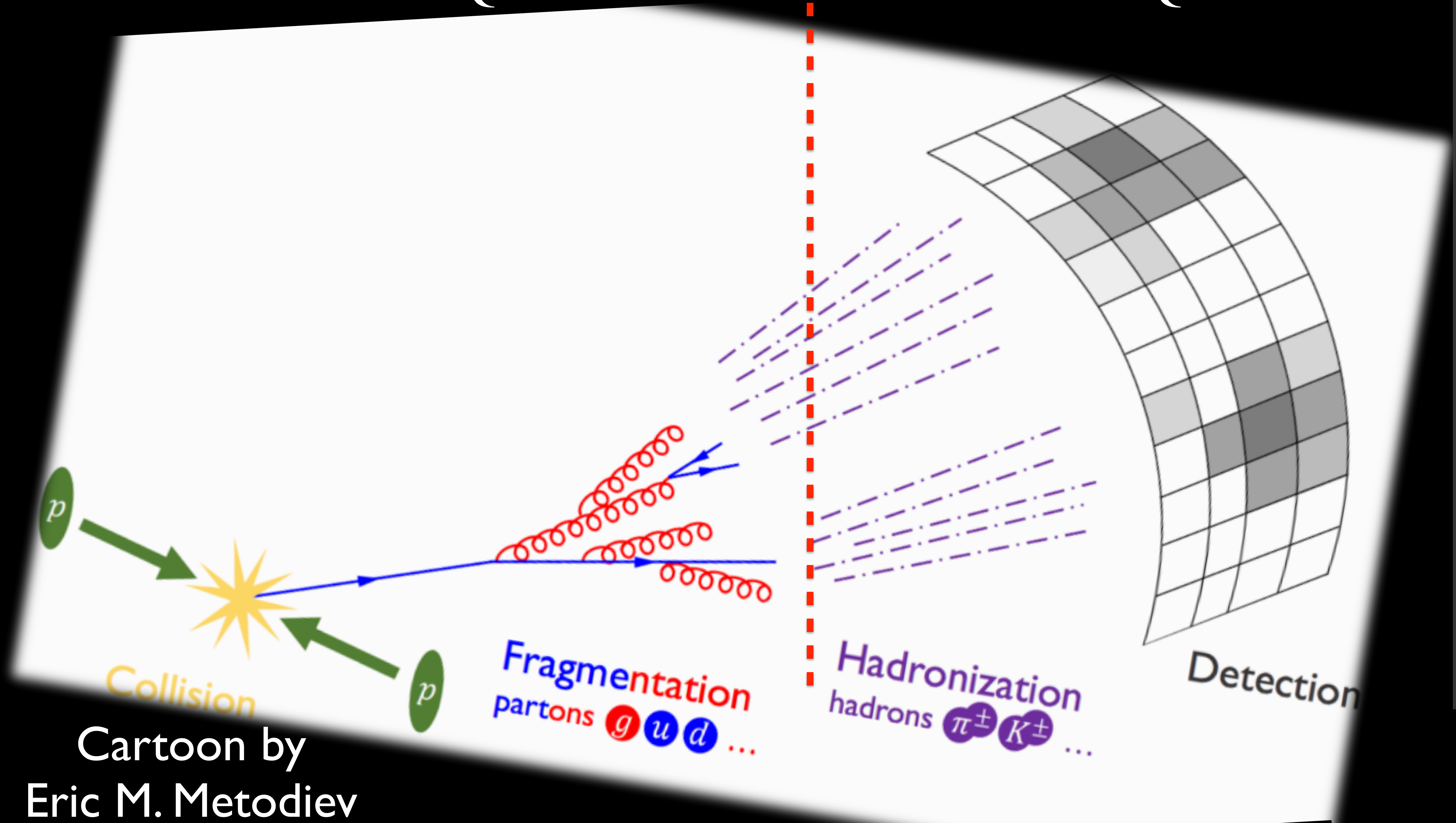

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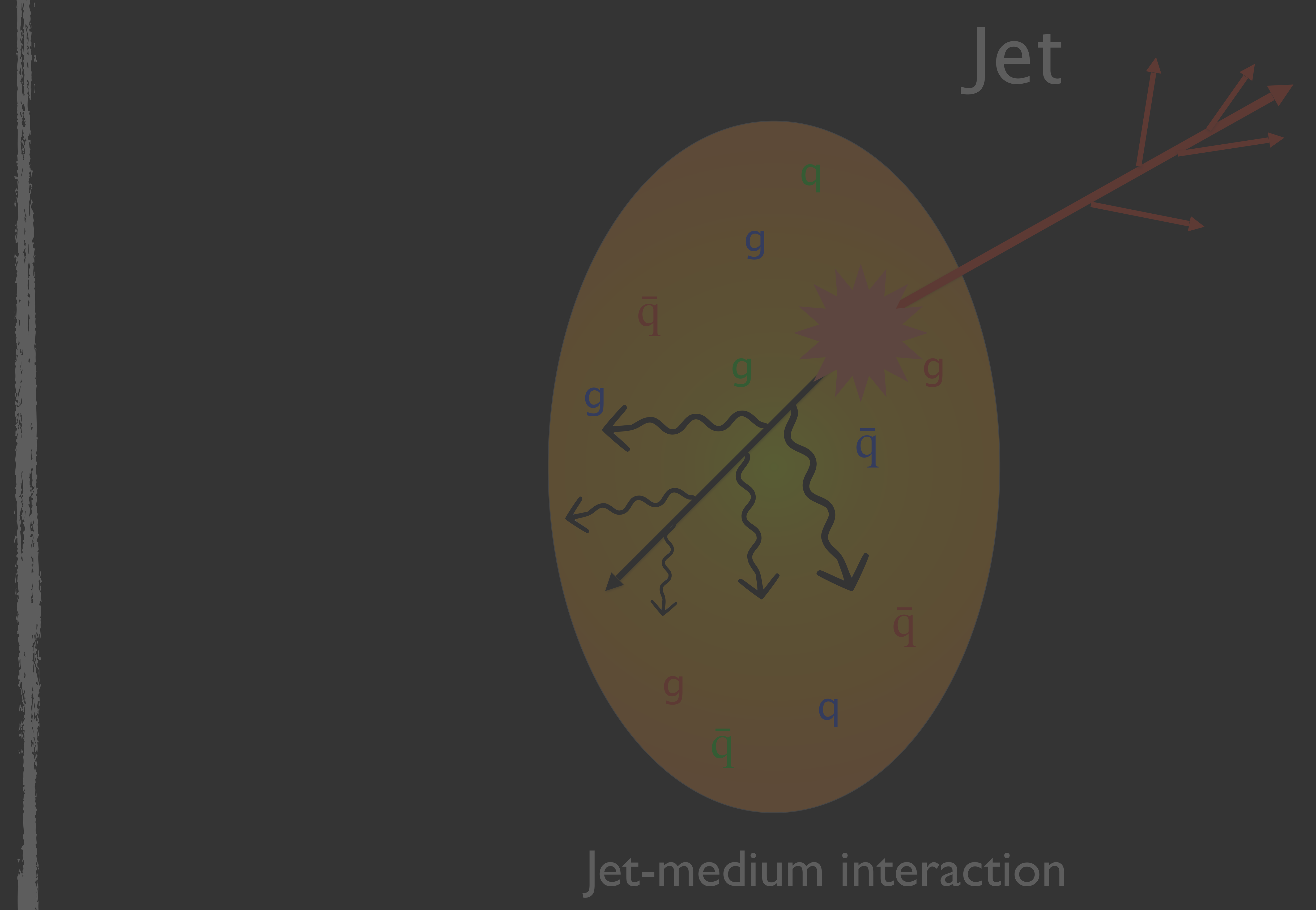
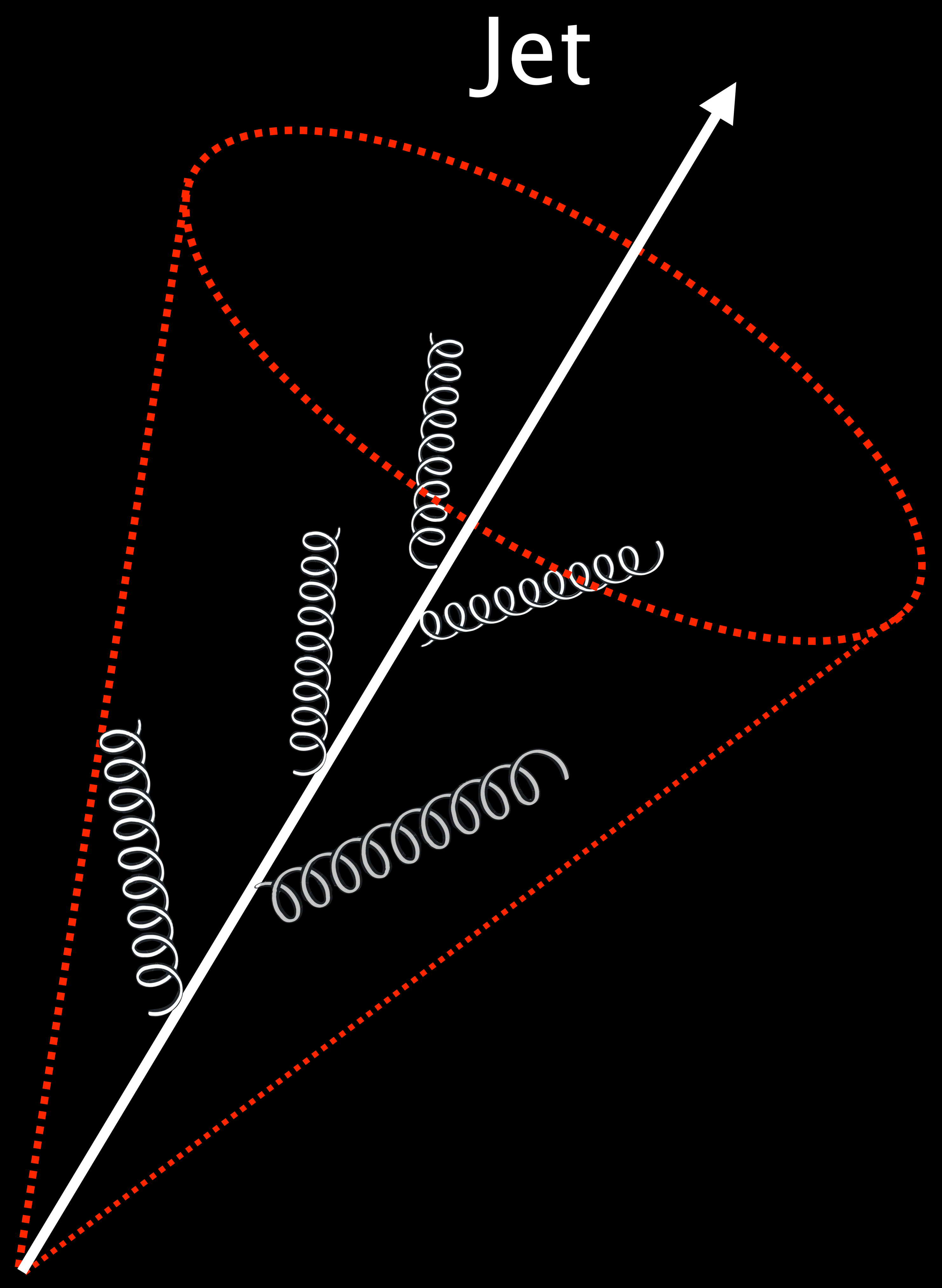
Properties of QGP



Baseline measurement for QGP studies in pp

Study of jet substructure in pp collision

What is jet substructure?

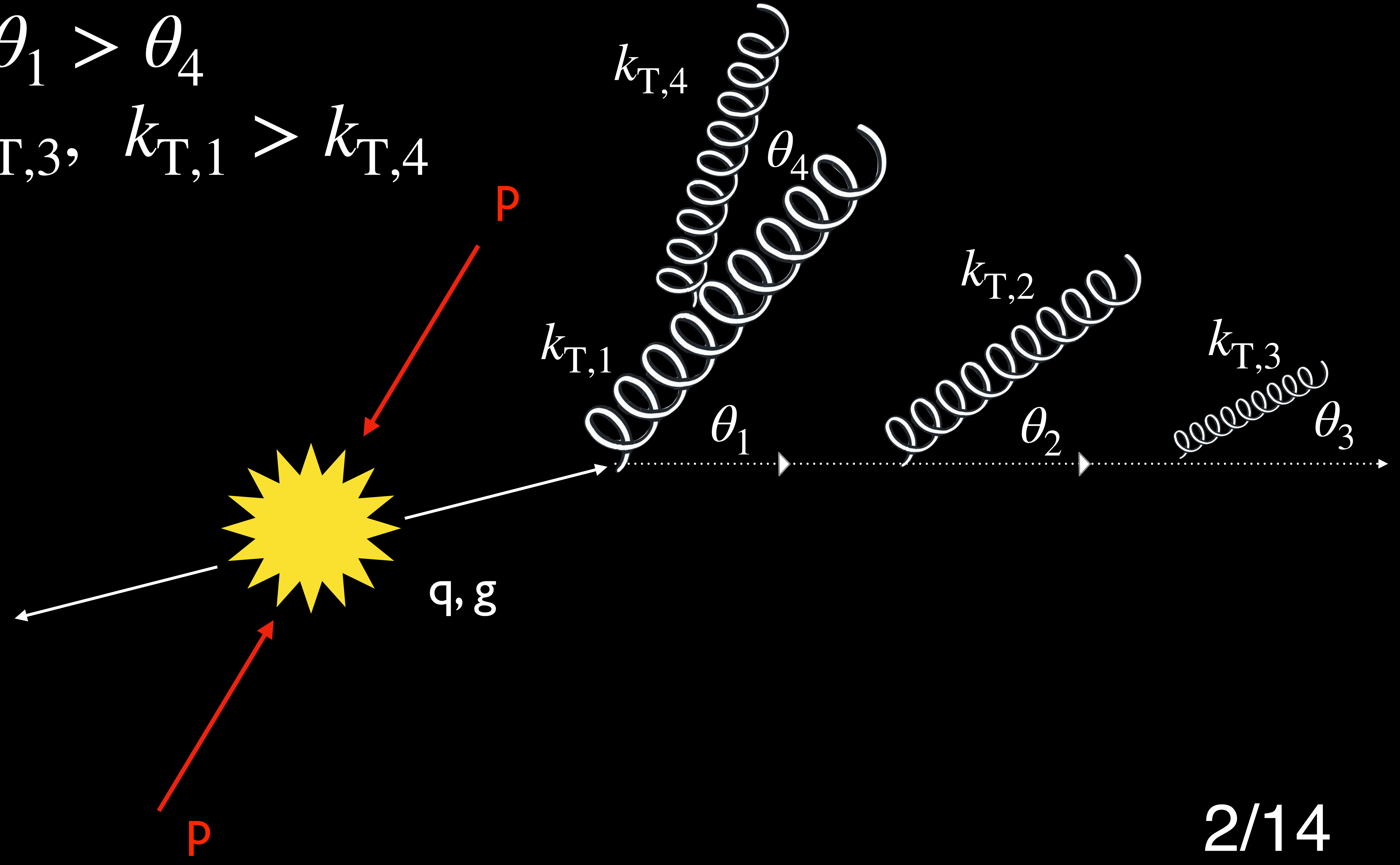


- Internal dynamics of particles constituting jets in angular + momentum space

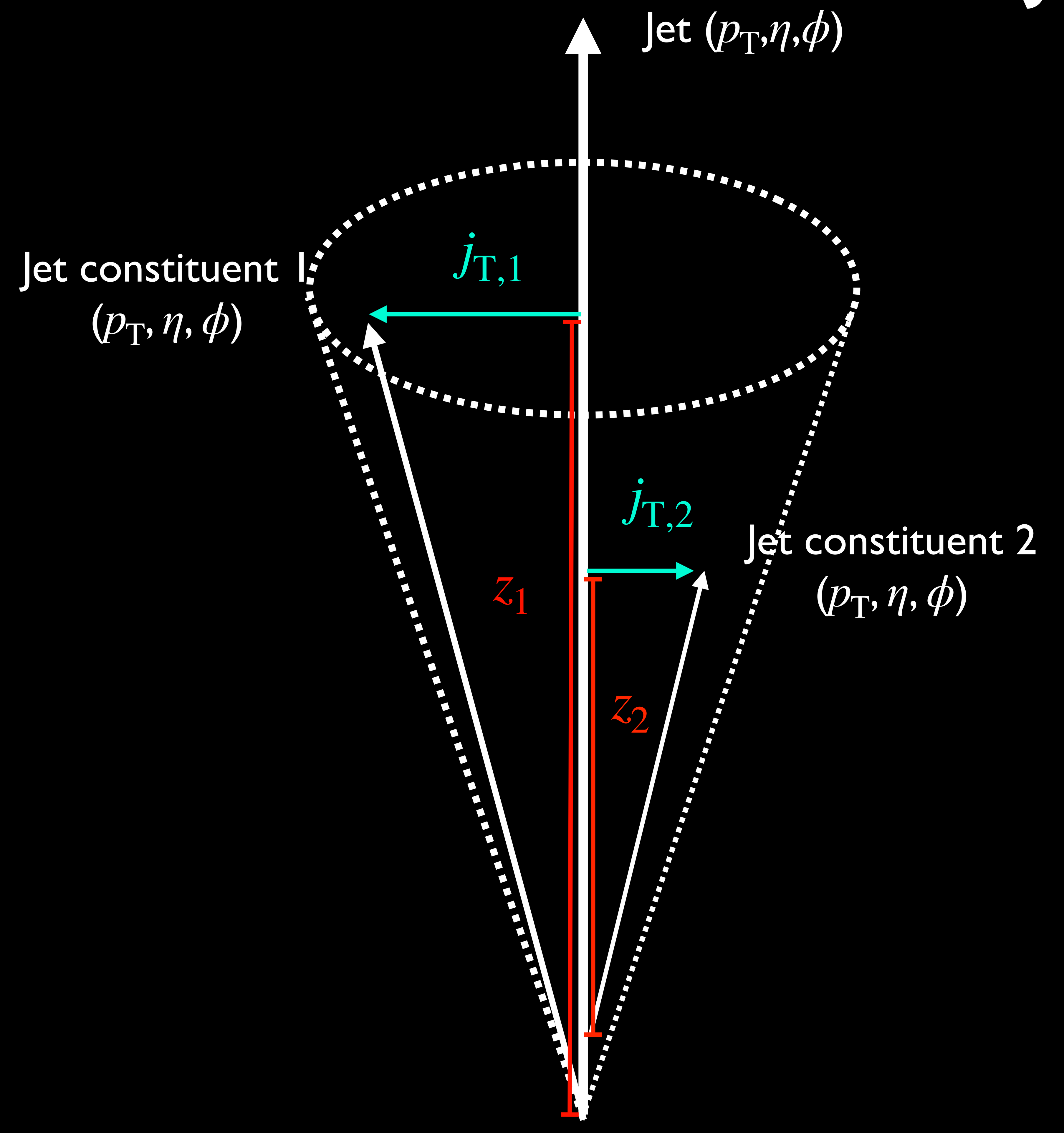
QCD angular ordering

- QCD prefers smaller emitting angles and lower virtuality with increasing number of emitting gluons
- Called angular ordering

$$\theta_1 > \theta_2 > \theta_3,\ \ \theta_1 > \theta_4$$
$$k_{T,1} > k_{T,2} > k_{T,3},\ \ k_{T,1} > k_{T,4}$$



Multi-differential charged-particle jet fragmentation observables



- $j_T = \dfrac{|\vec{p}_{jet} \times \vec{p}_{track}|}{|\vec{p}_{jet}|}$
- $z = \dfrac{\vec{p}_{jet} \cdot \vec{p}_{track}}{p^2_{jet}}$

Understanding of QCD jet evolution

- Test our current understanding of QCD theory by measuring differential distributions of charged-particle jet fragments in pp collisions and comparing results to model predictions
- Naive expectation that dominance of high j_T, z components at the early stage (Larger angle) and low j_T, z components at the late stage (Smaller angle)
- Possibly disentangle jet fragmentation and hadronisation processes

Study of jet substructure in small systems

ALICE

Previous ALICE analysis on jet substructure

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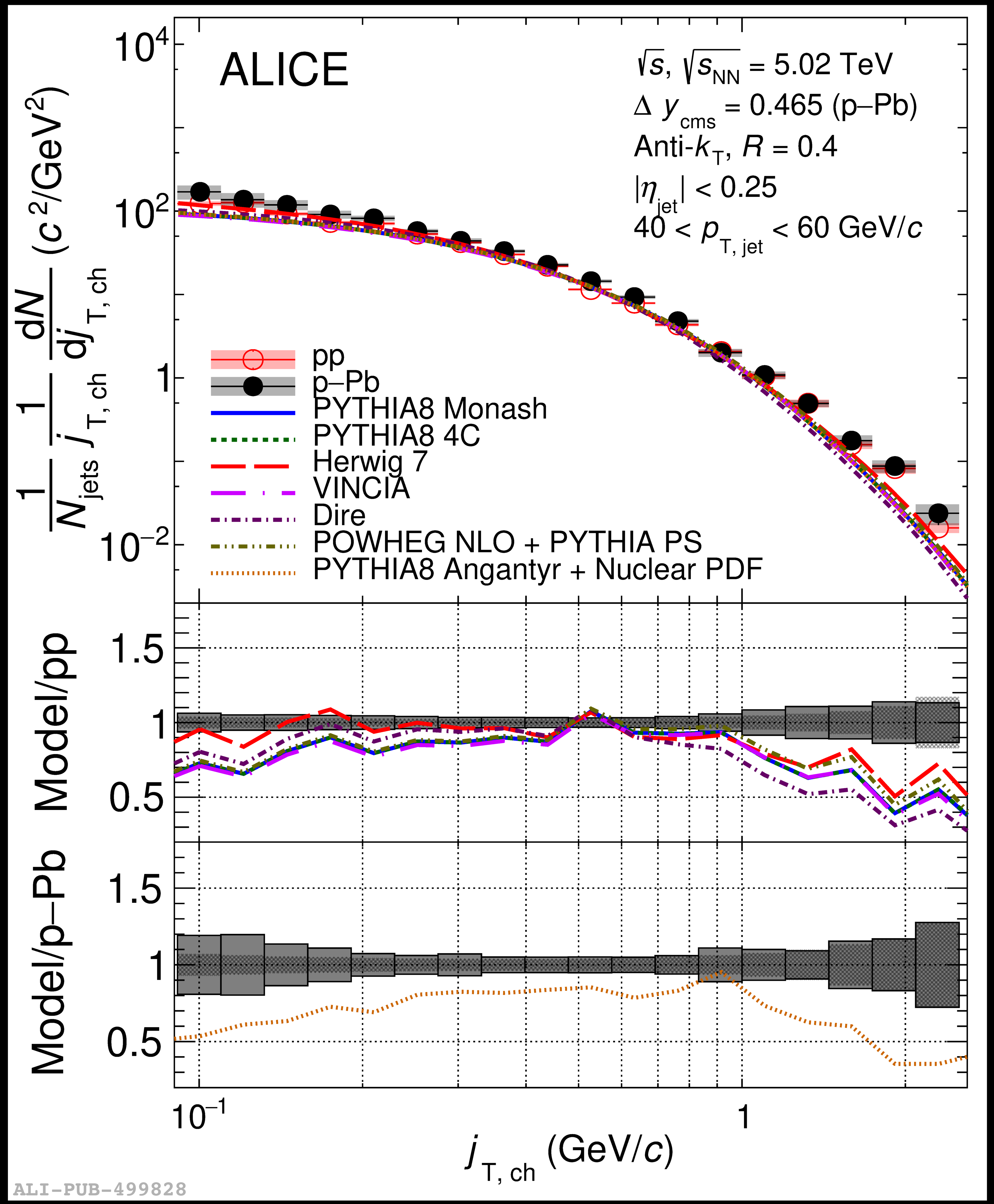
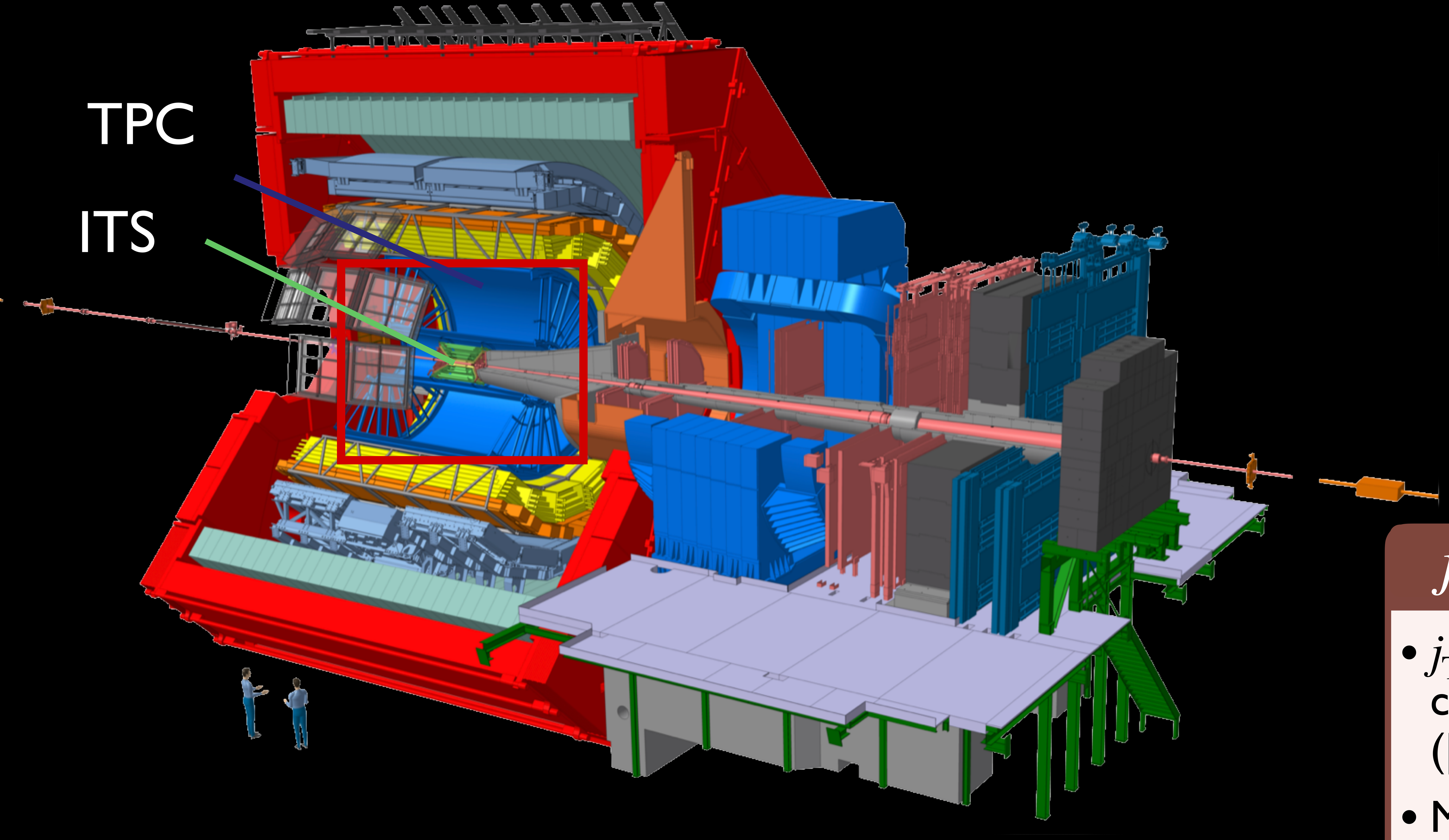


- Previous ALICE publication of the full jet j_T distributions in pp and p-Pb collisions was inclusive in z
- This analysis extends the previous study to be differential in z to further explore the parton shower process of the jet evolution process
- j_T distributions in inclusive ($0 < z \leq 1$), low ($0 < z < 0.2$), mid ($0.2 < z < 0.4$) and high ($0.4 < z \leq 1$) z ranges have been investigated
- The study is performed with a new analysis framework
  - Full jets → Charged-particle jets
  - 2-D unfolding → 3-D unfolding

ALICE experiment

2017 LHC pp collisions at $\sqrt{s}$ = 5.02 TeV



ALICE detector

Jet reconstruction

- Charged-particle jets in $|\eta| < 0.5$ are reconstructed with charged tracks in the ITS/TPC ($p_{\mathrm{T}} > 0.15$ GeV/c and $|\eta| < 0.9$, $0 < \phi < 2\pi$)
- Anti-k_{T} algorithm with $R = 0.4$

j_{T}, z calculation

- j_{T} and z are calculated with charged-particle jets and constituent charged tracks reconstructed in ALICE ITS/TPC ($|\eta| < 0.9$, $0 < \phi < 2\pi$)
- Minimum p_{T} = 0.15 GeV/c for charged particles

- The result j_{T} distributions are compared to various parton-shower models to test our current understanding on the QCD theory

MC simulation models

ALICE

PYTHIA8 webpage
: https://pythia.org/

PYTHIA 8

- Initial hard scattering
  pQCD calculation at Leading-Order (LO)
- Partonic showers
  Momentum ordered parton shower
- Hadronisation
  Gluon fragmentation
  (Lund string fragmentation)
- Underlying event
  Multi Parton Interaction (MPI)

Comput. Phys. Commun. 191, 159-177 (2015).

Herwig webpage
: https://herwig.hepforge.org/

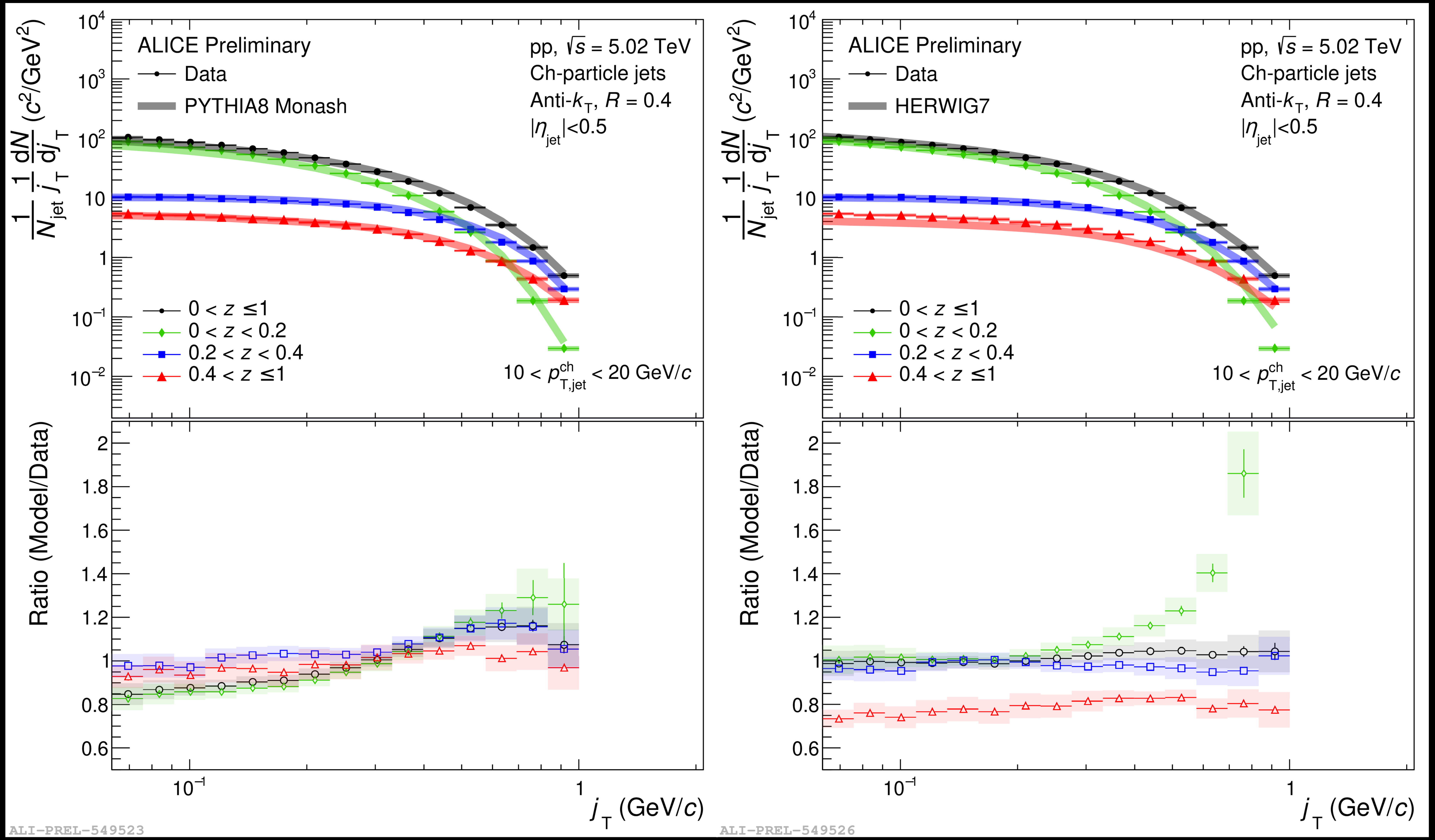
HERWIG 7

- Initial hard scattering
  pQCD calculation at Next-to-Leading-Order (NLO)
- Partonic showers
  Soft gluon interference via angular ordering
- Hadronisation
  Cluster approach
- Underlying event
  Multiple partonic scatterings

V

Results & model comparison

ALICE

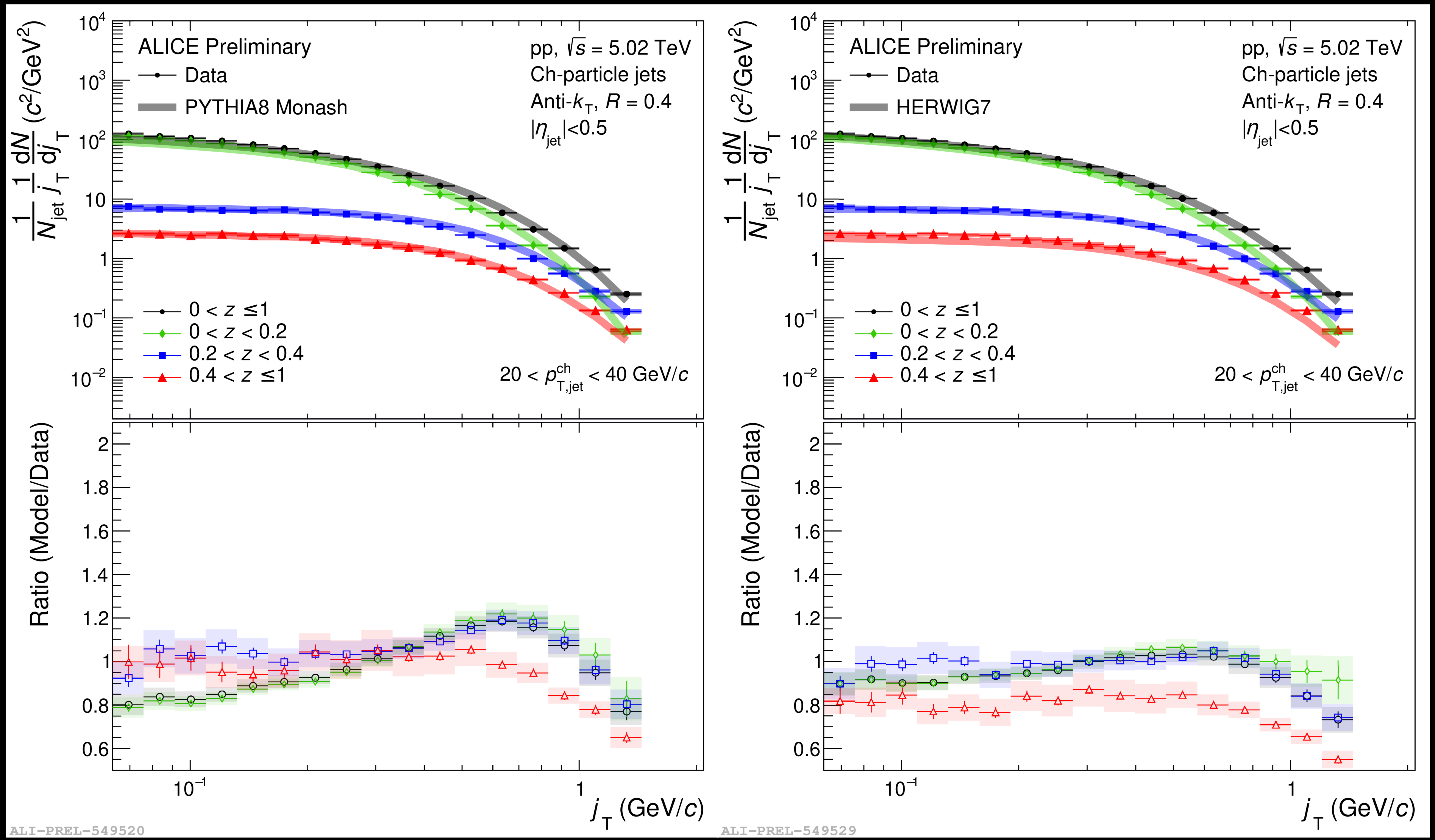


$10 < p_{T,jet} < 20$ GeV/c

- The j_T distributions for different $p_{T,jet}$ compared with PYTHIA8 Monash and HERWIG 7 for different z ranges
- PYTHIA8 shows the general trend of an increase below 1 at low j_T, crossing above 1 at mid j_T, and decreasing at high j_T in inclusive and low z
- PYTHIA8 shows consistency with the data in mid and high z regions for the j_T under 1
- Herwig underestimate the high z region and overestimate the low z, high j_T region

Results & model comparison

ALICE

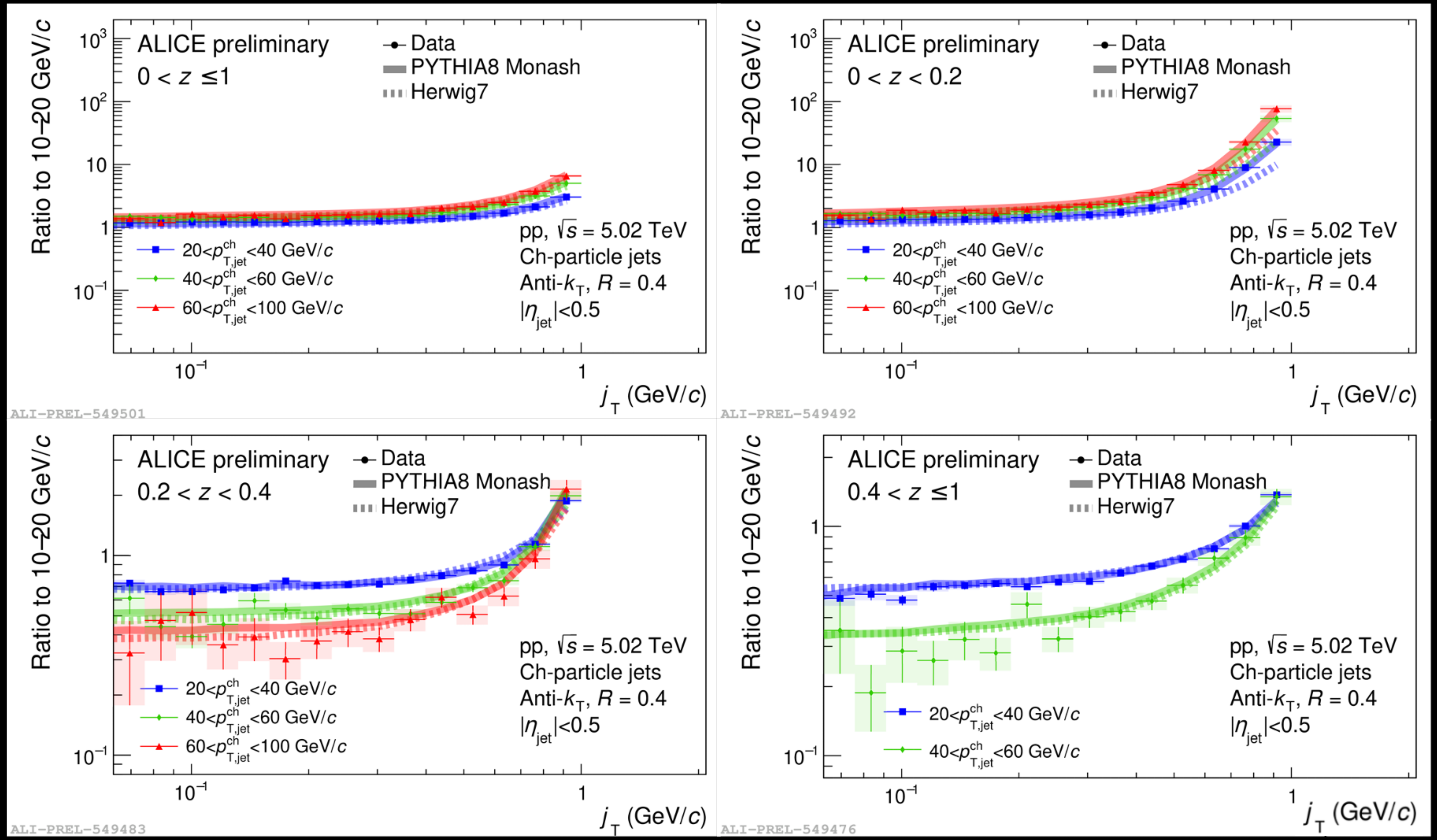


$20 < p_{T,jet} < 40$ GeV/c

- The j_T distributions for different $p_{T,jet}$ compared with PYTHIA8 Monash and HERWIG 7 for different z ranges
- PYTHIA8 shows the trend of an increase below 1 at low j_T, crossing above 1 at mid j_T, and decreasing at high j_T in inclusive and low z
- PYTHIA8 shows consistency with the data in mid and high z regions for the j_T under 1
- Herwig underestimate the high z region and overestimation as lower $p_{T,jet}$ was disappeared

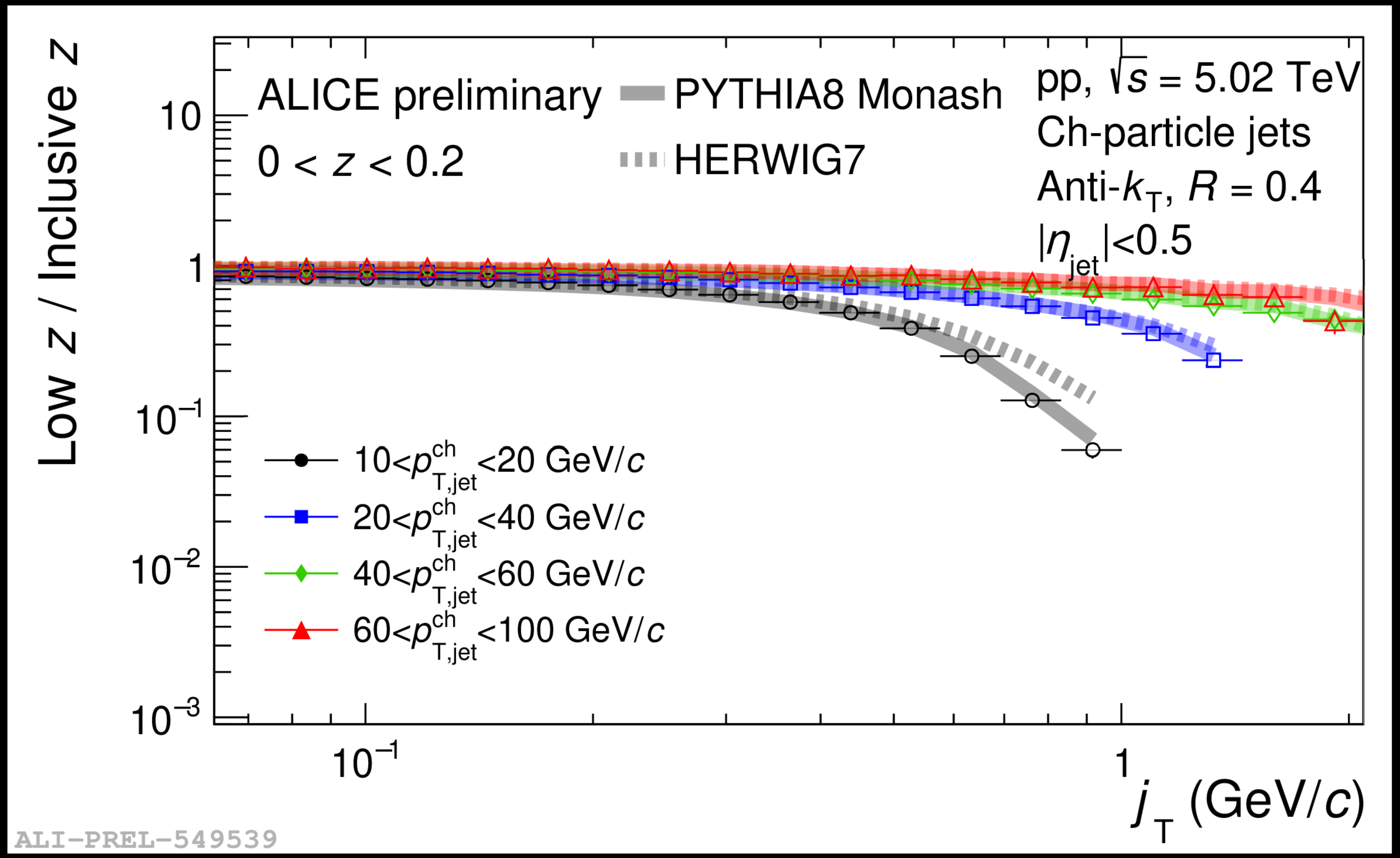
Results & model comparison

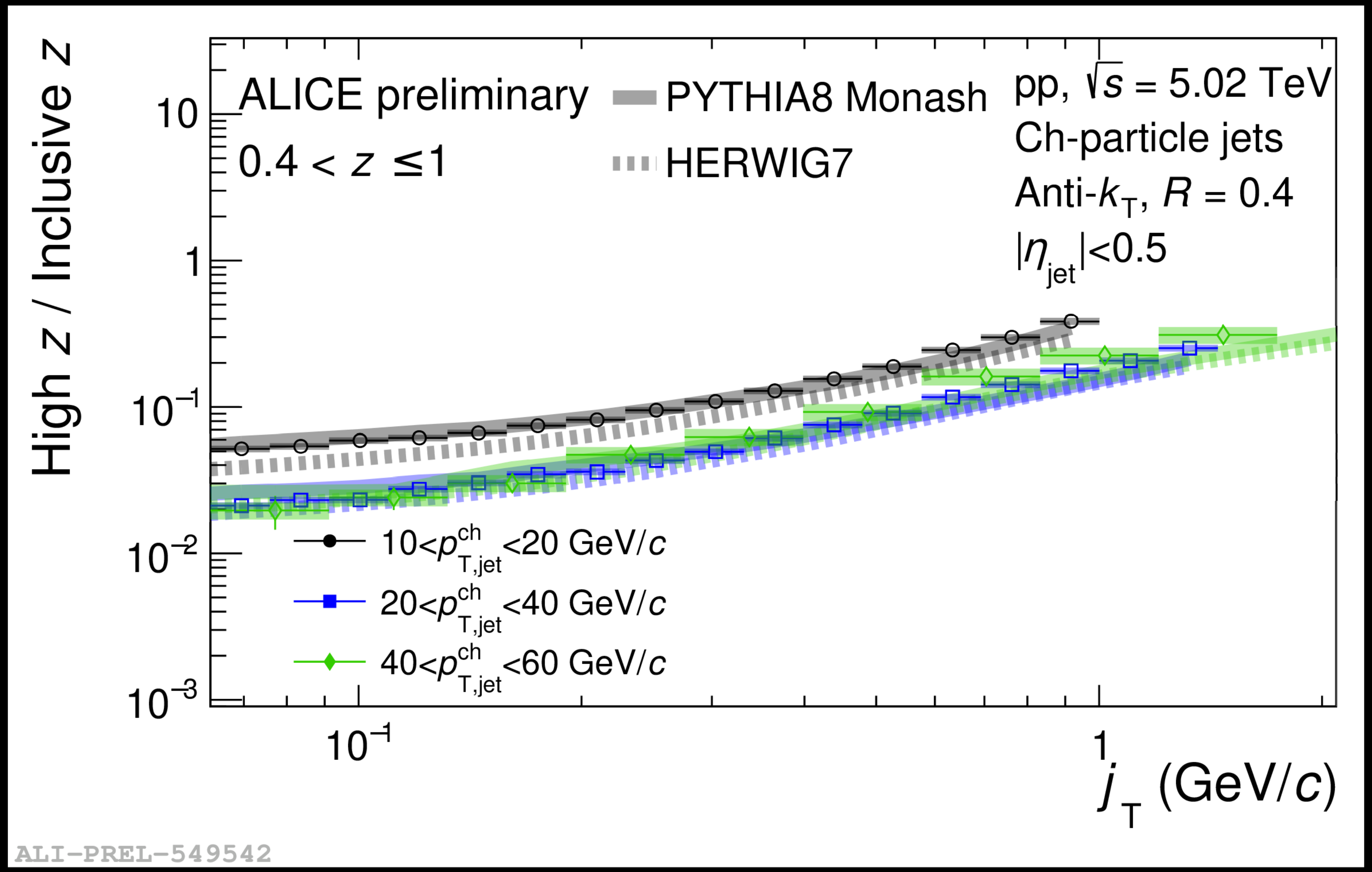
Jet p_T dependence



- j_T distributions in other $p_{T,jet}$ regions compared to the 10-20 GeV/*c*
- While both models couldn't describe the j_T distribution, they have good descriptions on the trend of the ratio in all z ranges
- Indicate the difference between the model and data is not from the $p_{T,jet}$ dependence
- Comparisons with MC generators set constraints on models

Differential to inclusive z ratio



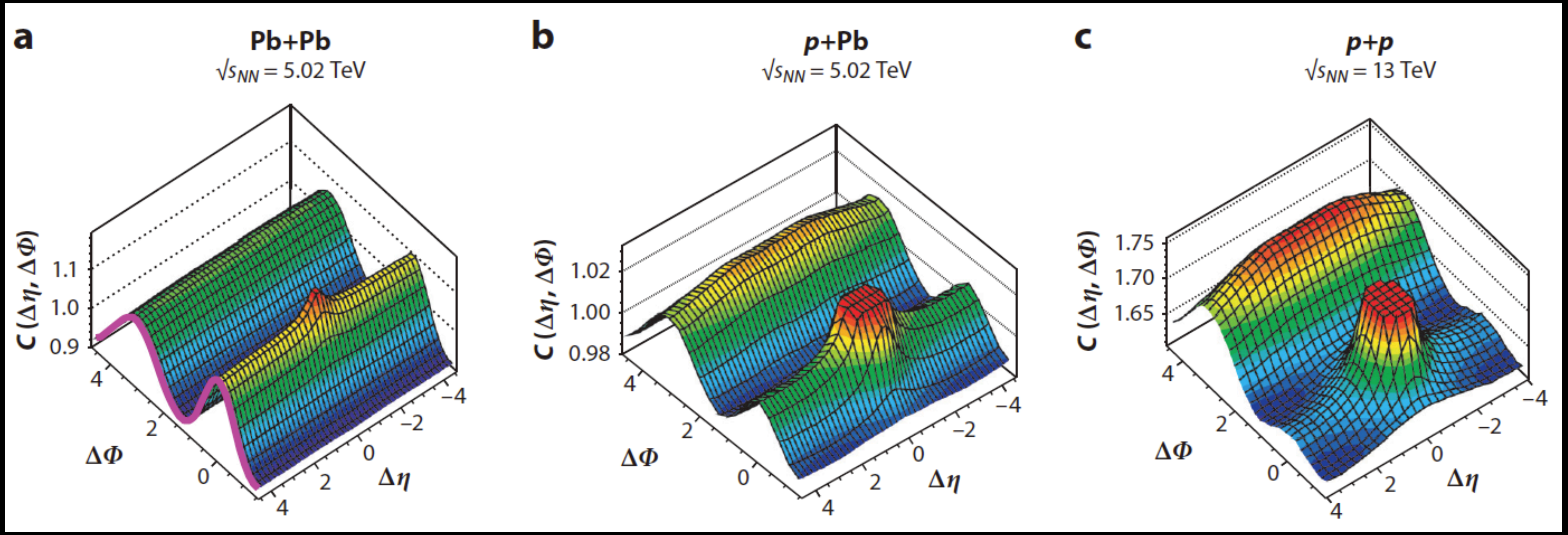


- Low j_T components are dominant in the low z, high j_T components are dominant in the high z which is consistent with QCD angular ordering
- Models qualitatively explain the data

Study of jet in small systems

Clear near-side long-range correlation has been observed in high multiplicity pp and p–Pb collisions!

Any modification of jets in such collision systems?



Annu. Rev. Nucl. Part. Sci. 2018. 68

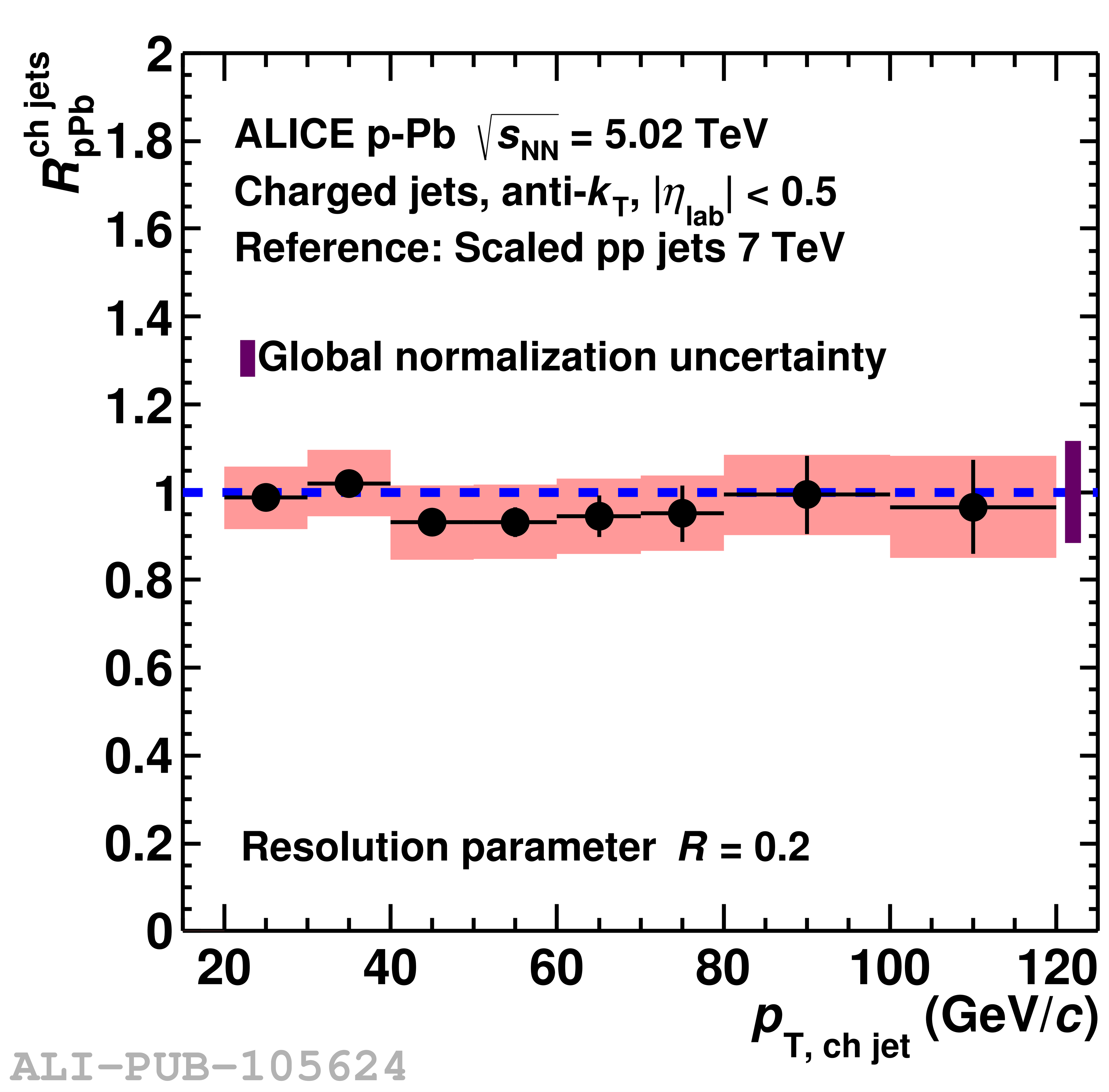
Study of jet in small systems

How to investigate jet modification in small collision systems?

Jet yield modification

Jet deflection (Dijet acoplanarity)

Jet substructure modification

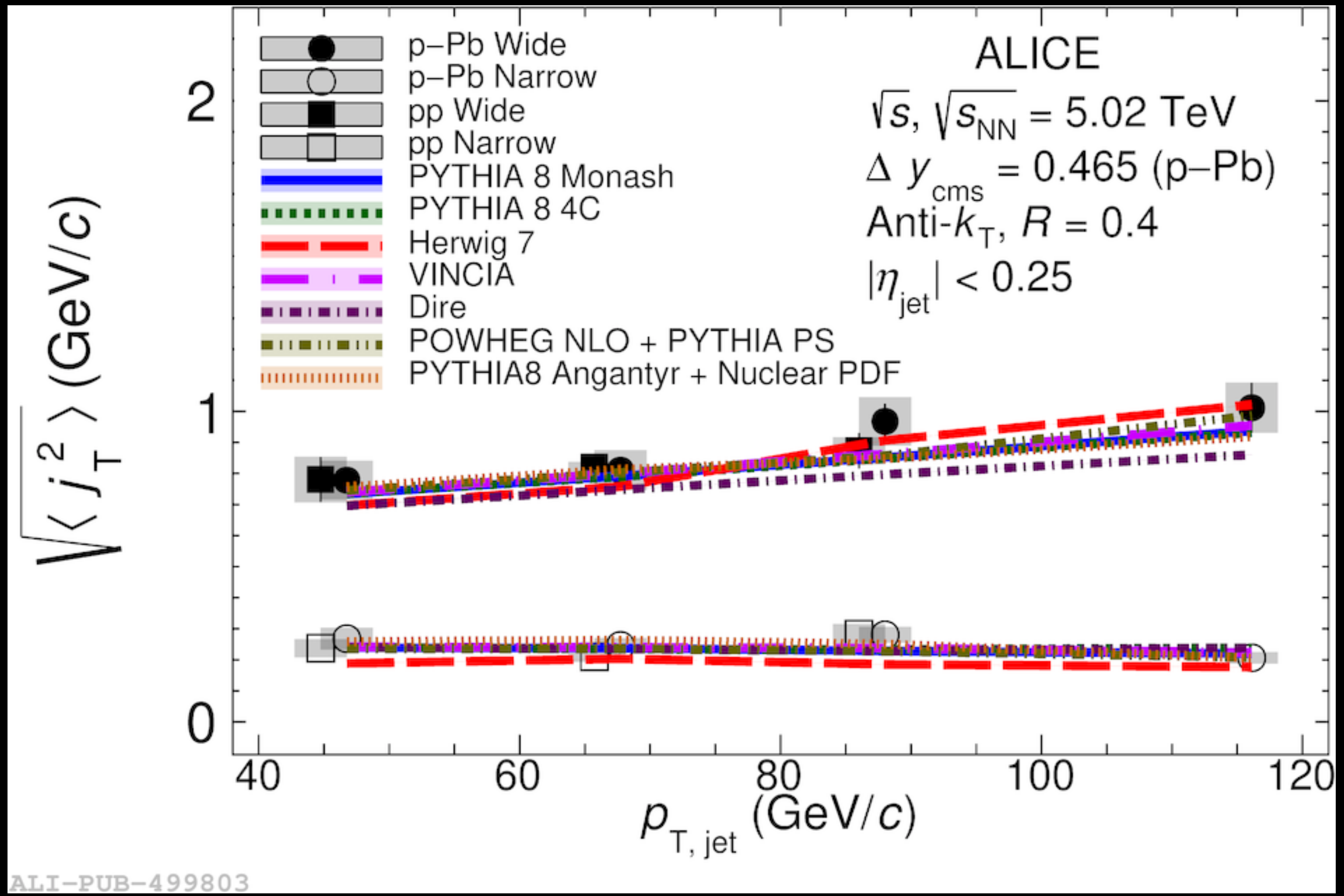


Physics Letters B 749 (2015) 68-81

What about jet substructure modification?"

Two-component fit

Two-component fit



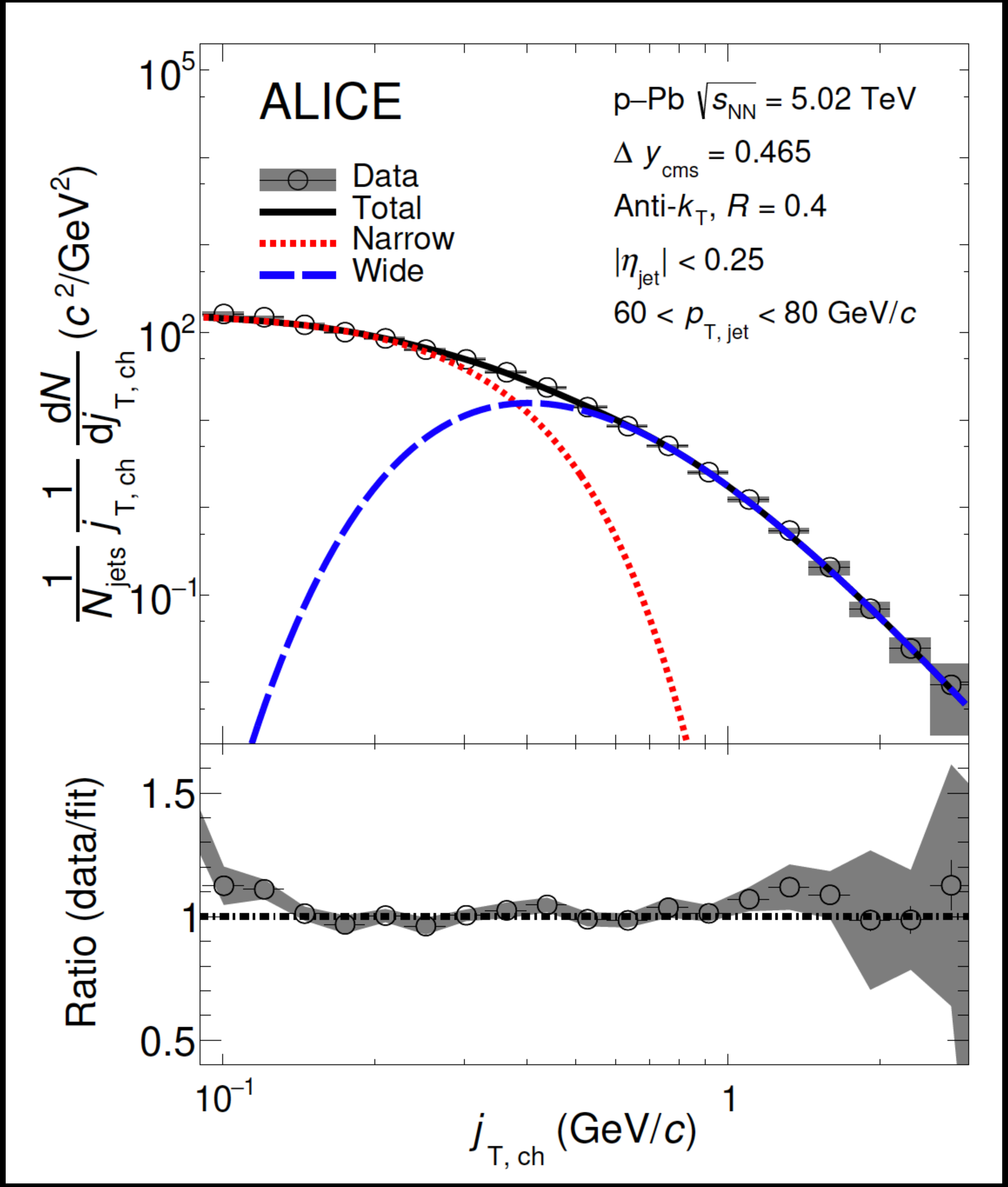
Hadronisation

Gaussian distribution centered at j_T = 0 GeV/c for the lower j_T

$$\frac{1}{N_{\text{jets}}} \frac{dN}{j_{T,ch} dj_{T,ch}} = \frac{B_2}{B_1\sqrt{2\pi}} e^{-\frac{j_T^2}{2B_1^2}} + \frac{B_3 B_5^{B_4}}{\Gamma(B_4)} \frac{e^{-\frac{B_5}{j_T}}}{j_T^{B_4+1}}$$

Inverse gamma function for j_T above 1 GeV/c

Fragmentation



Summary & Outlook

ALICE

- j_{T} has been measured in various z regions at $\sqrt{s}$ = 5.02 TeV pp collisions with ALICE to test our current understanding of QCD theory
- Descriptions of models (PYTHIA 8, HERWIG 7) are different in the different kinematic ranges and are not from the $p_{\mathrm{T,jet}}$ dependence
- Results are expected to constraints models
- Results are consistent with QCD angular ordering
- To disentangle partonic showers and hadronization processes, two-component fitting method has been implemented
- Results will be the baseline measurement for further research in high-multiplicity pp and p–Pb to investigate possible jet-medium interaction in small collision systems

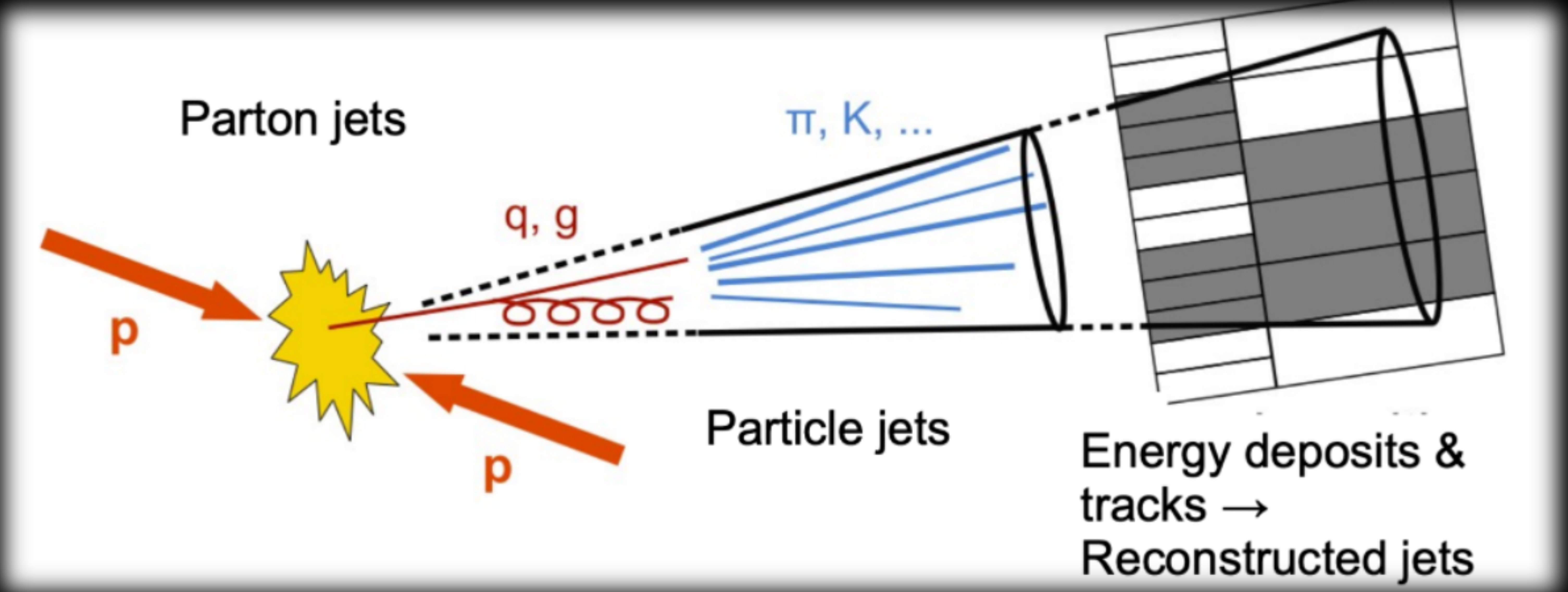
Thank you!

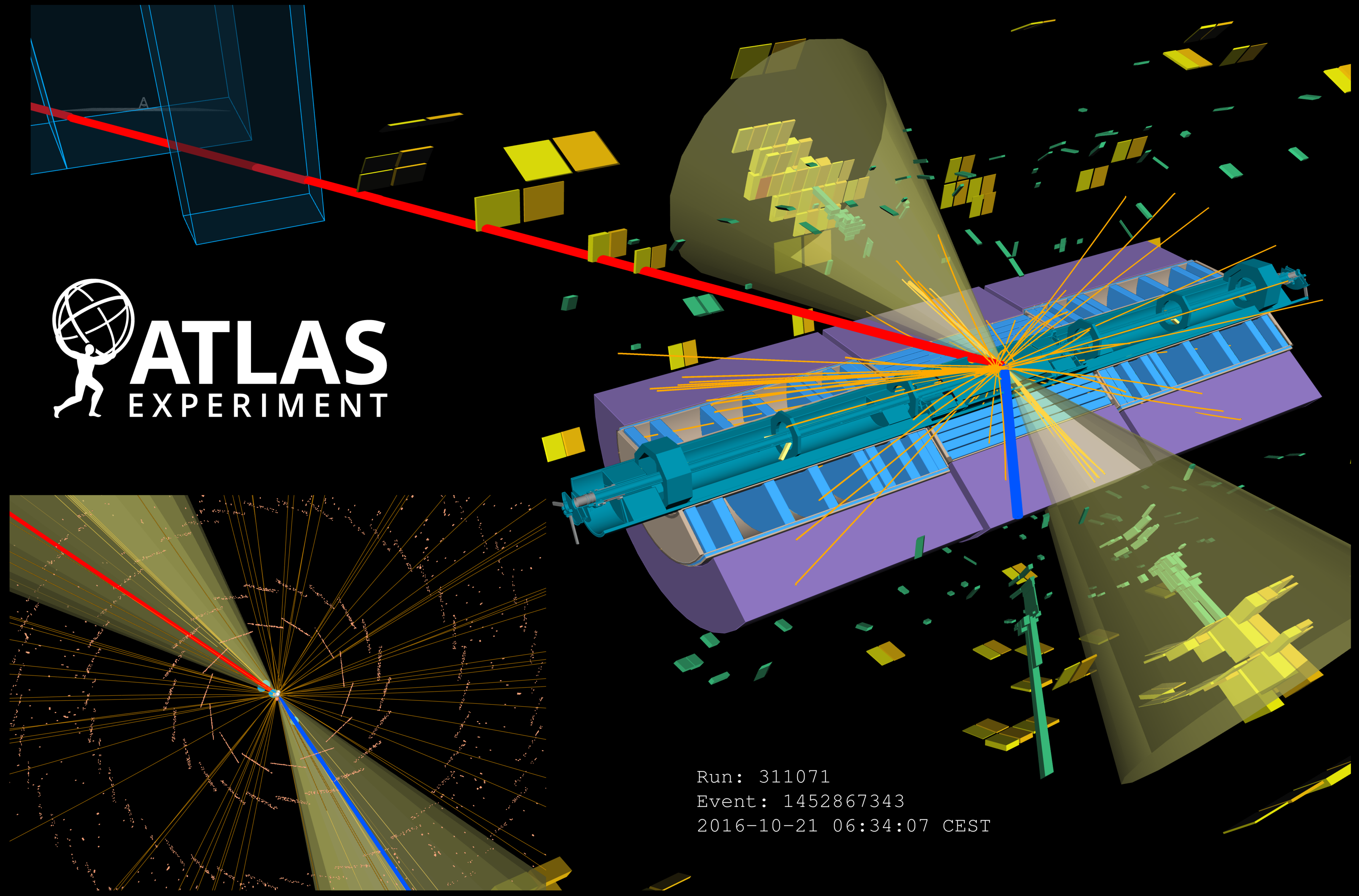
Back-up slides

ALICE

What is a jet?

- Jets are clusters of stable particles resulting from fragmentation of hard scatter partons

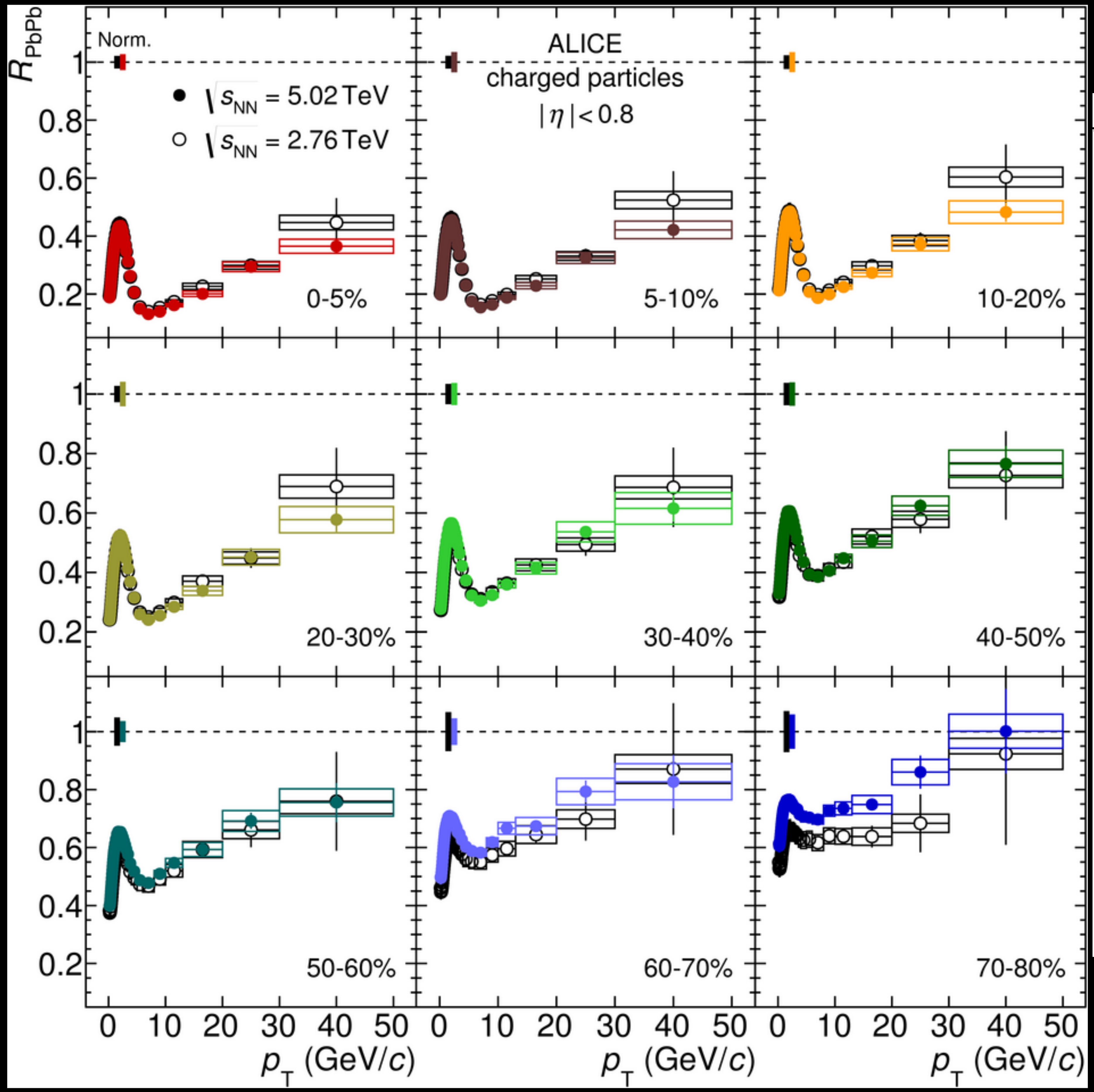




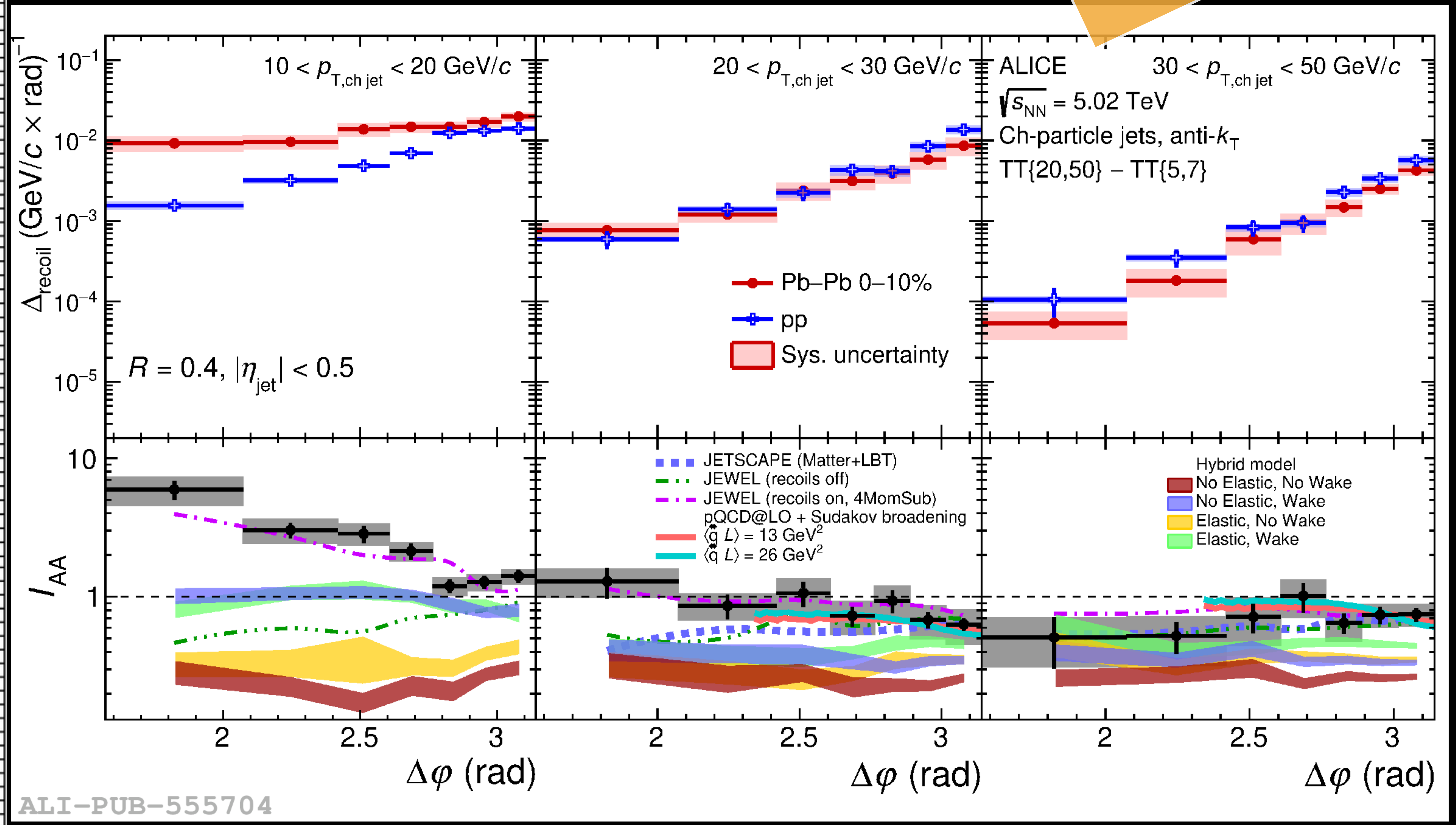
Jet quenching in the QGP medium

Jets are one of the most effective probes to study the properties of Quark-Gluon Plasma (QGP)

e. g. Jet quenching



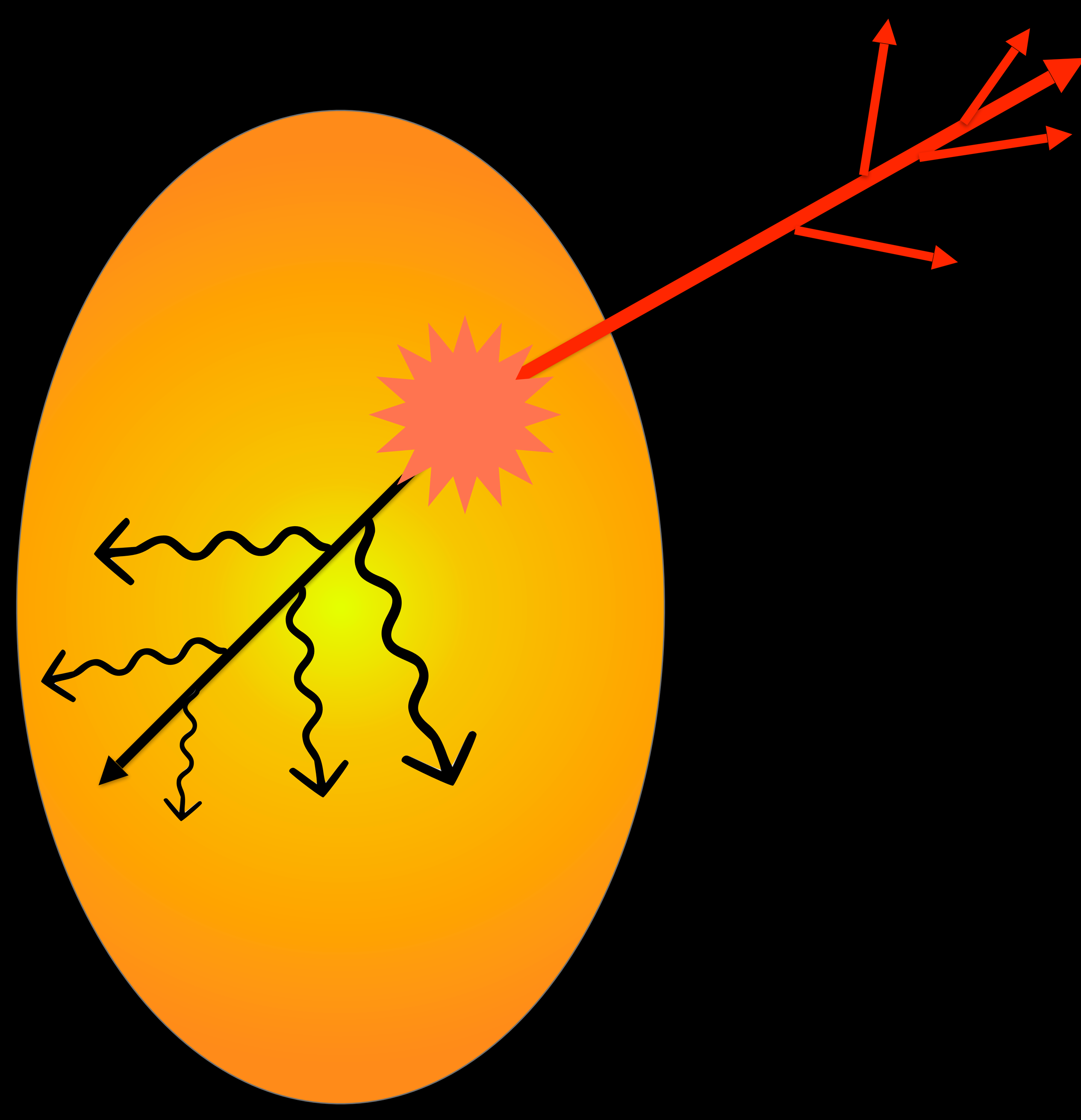
JHEP 11 (2018) 013



Friday, July 19 07,Heavy Ions Yaxian Mao

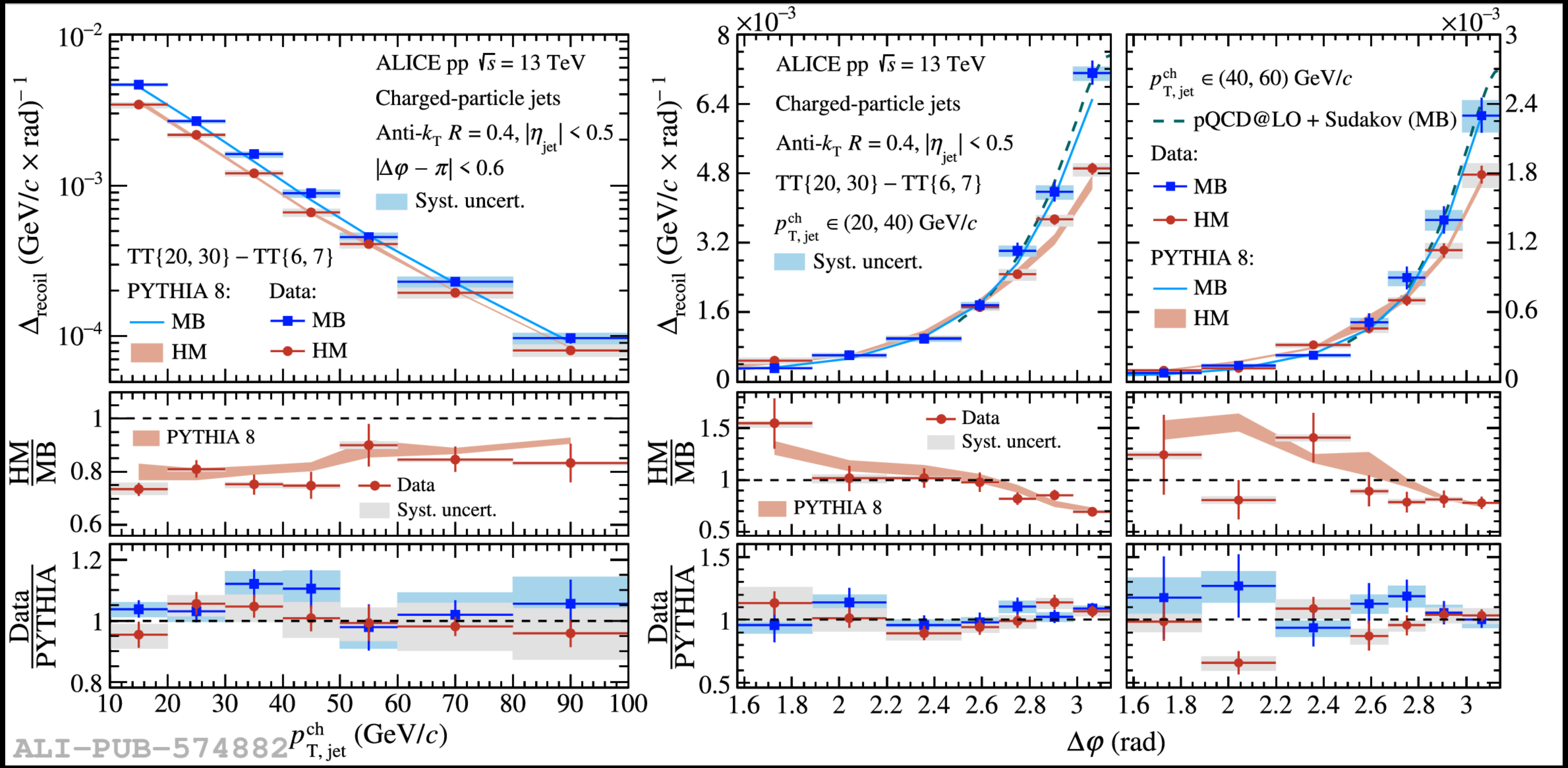
arXiv:2308.16131

Jet



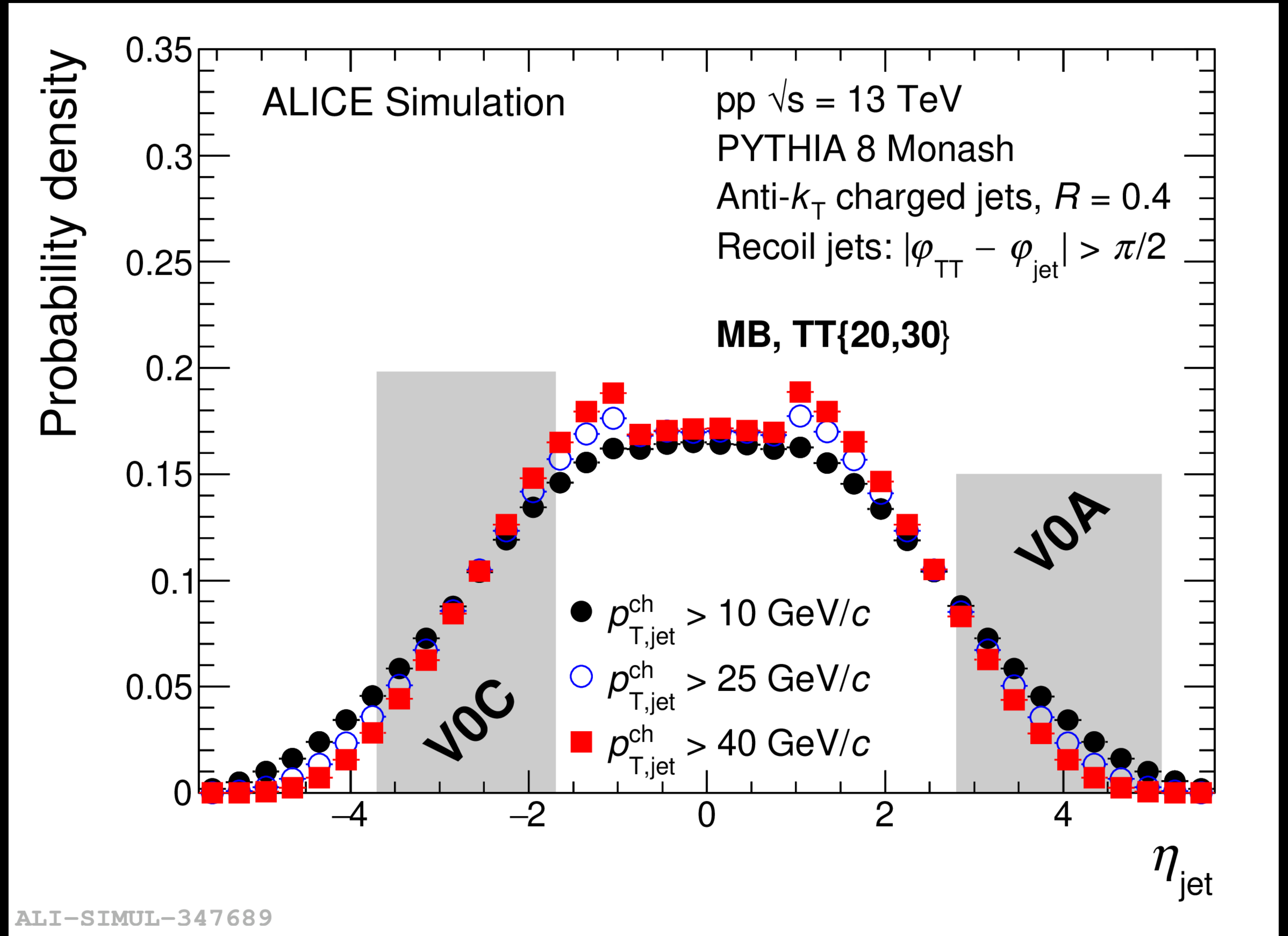
Jet-medium interaction

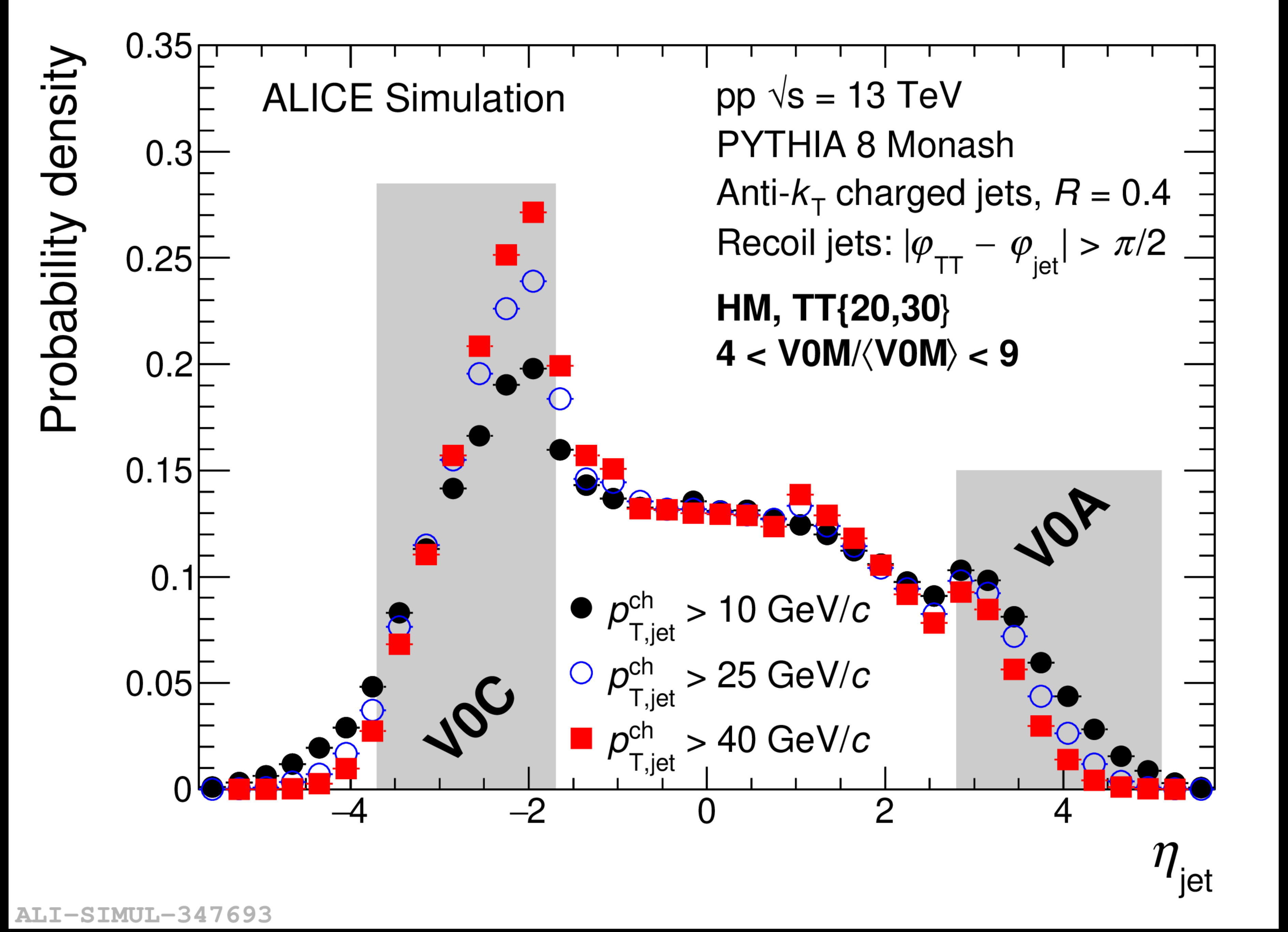
Hadron+jet coplanarity in ALICE



- Broadening of the h+jet acoplanarity distribution is observed in High-Multiplicity (HM) compared to Minimum-Bias (MB) events
- Could arise from jet quenching
- PYTHIA 8 Monash shows a good description on the suppression at HM which indicate the effect is not from the jet-medium interaction

HM selection bias



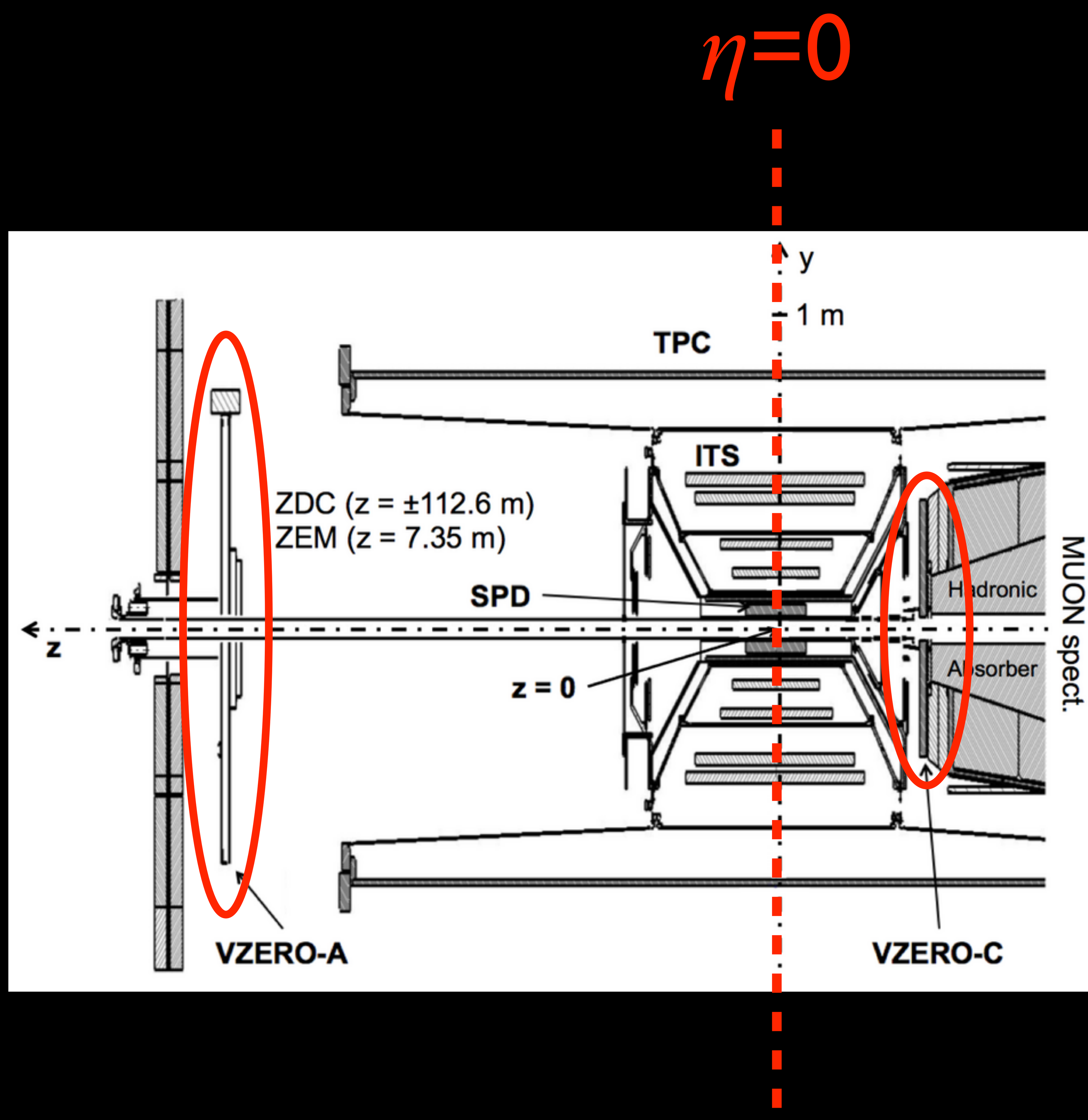


- η_{jet} distribution of jets in the recoil hemi-sphere from PYTHIA8 Monash

- Larger enhancement in V0C resulting from the asymmetric pseudo-rapidity acceptance of V0A and V0C in HM events
- The Bias is getting stronger with increasing $p^{ch}_{T,jet}$

- Broader jets are selected more in the V0C for HM events could hide the jet-medium interaction signal

- This bias should be taken into account for the further small system jet-medium interaction studies



Simultaneous correction

3-D Unfolding

- Correct detector effects that smear in jet p_{T}, z, and j_{T} by switching to a 3D unfolding procedure

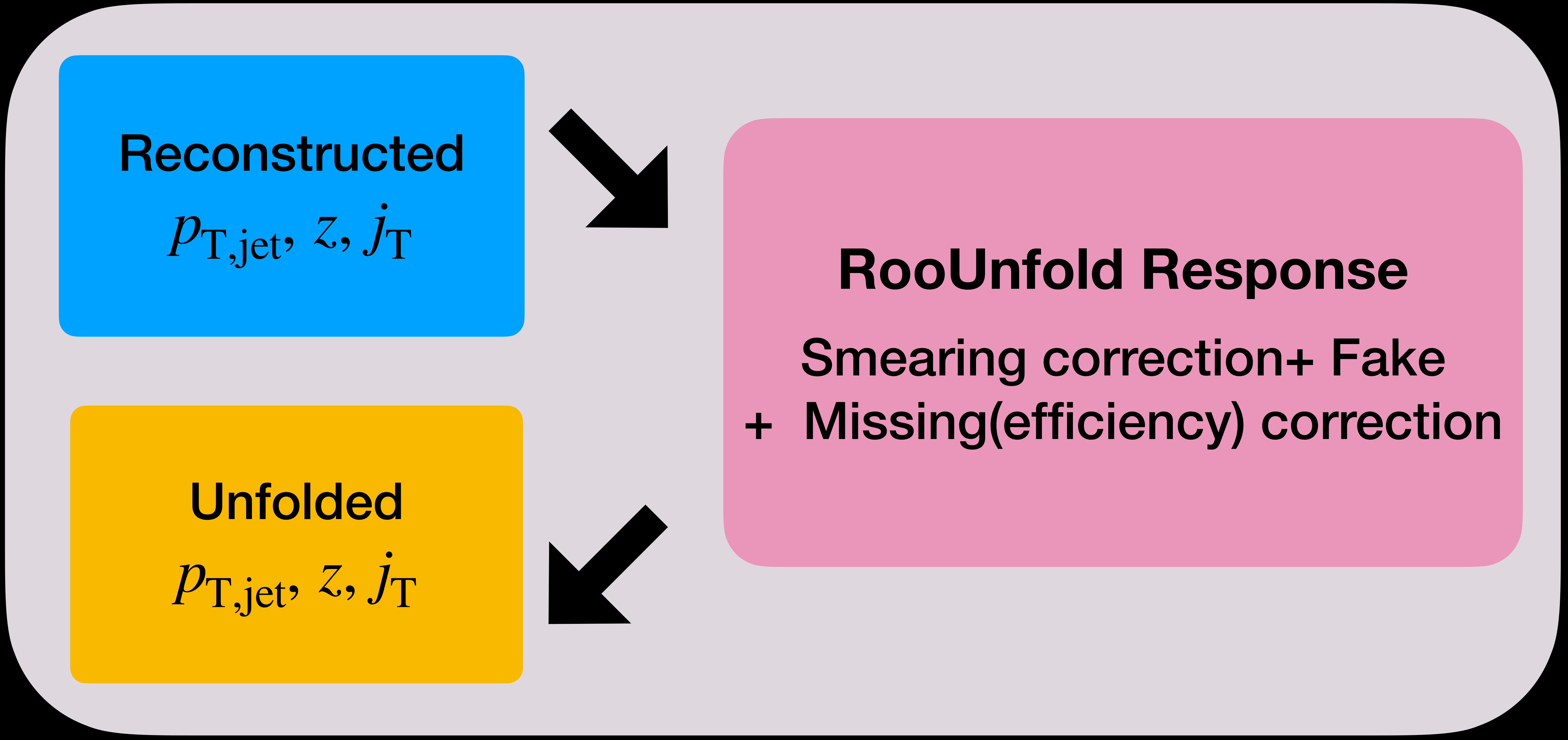
4-D response matrix (Previous analysis)

$$(p^{obs}_{\mathrm{T,\,jet}},\ j^{obs}_{\mathrm{T}},\ p^{true}_{\mathrm{T,\,jet}},\ j^{true}_{\mathrm{T}})$$

↓

6-D response matrix (This analysis)

$$(p^{obs}_{\mathrm{T,\,jet}},\ z^{obs},\ j^{obs}_{\mathrm{T}},\ p^{true}_{\mathrm{T,\,jet}},\ z^{true},\ j^{true}_{\mathrm{T}})$$



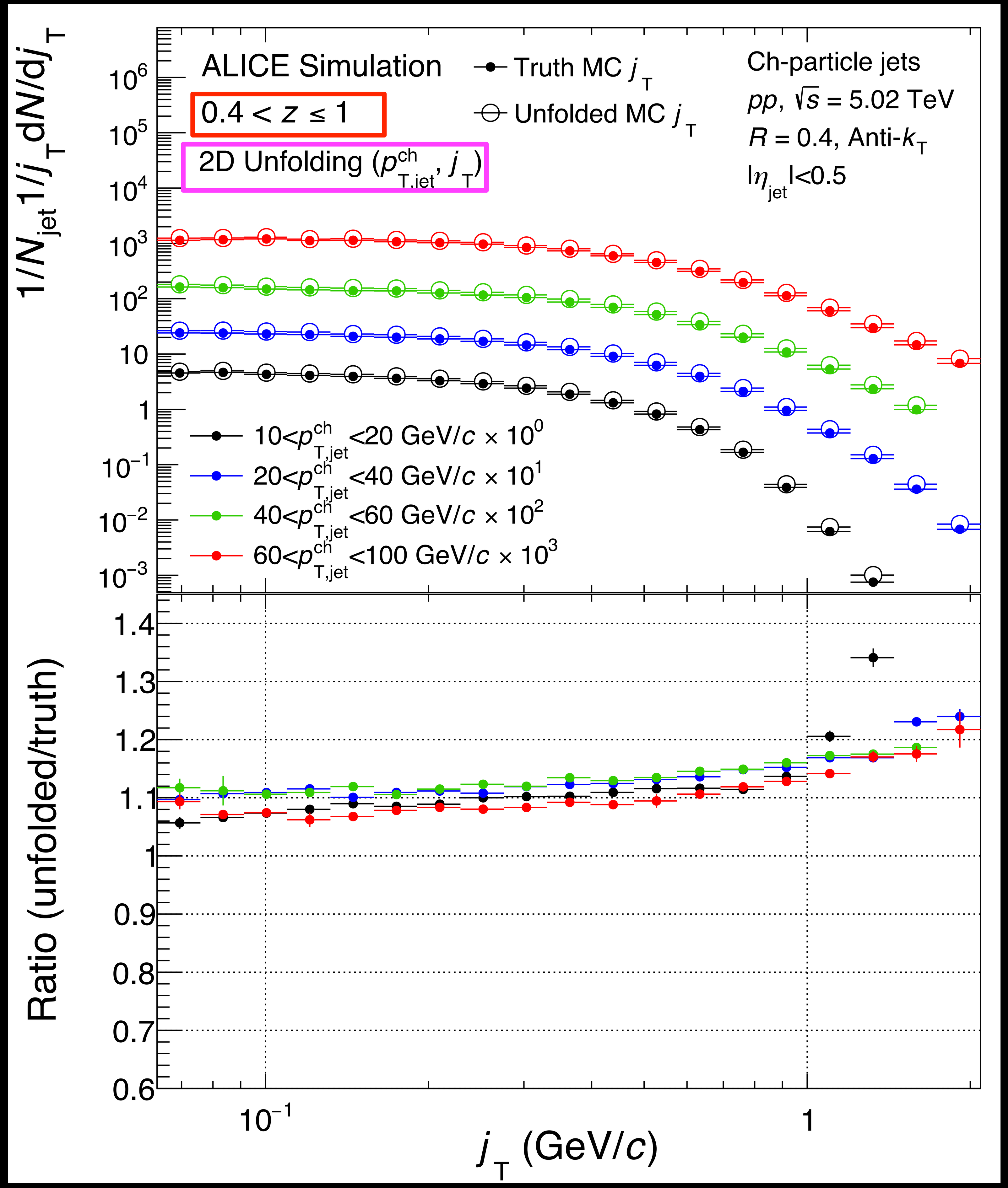
- Iterative Bayesian unfolding method
- Fake correction - Correct fake jets and fake tracks
- Missing corrections - Correct missing jets and missing tracks

Unfolding closure test

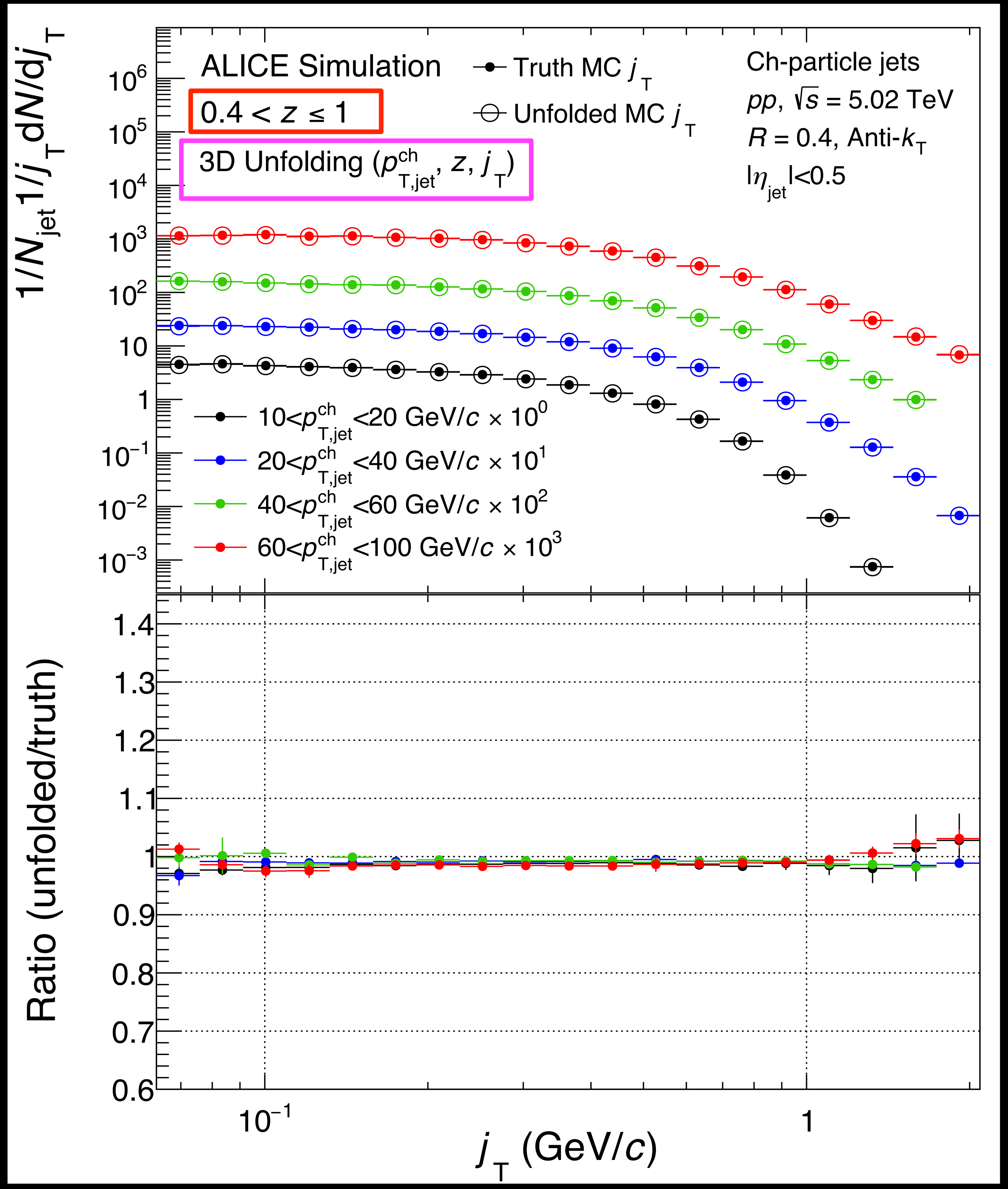
High z bin

$(0.4 < z \leq 1)$

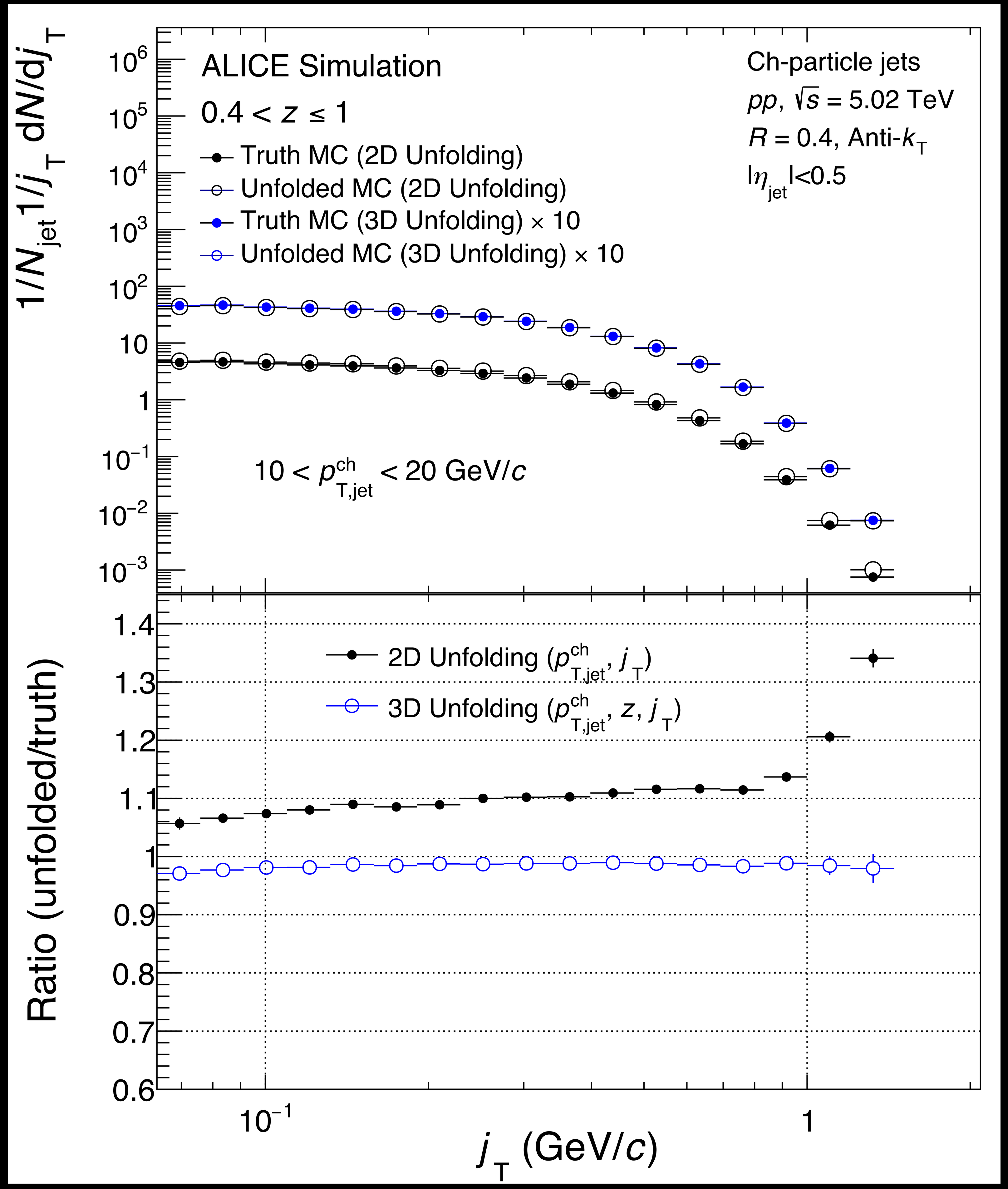
2-D unfolding



3-D unfolding



2-D vs 3-D



- 2-D and 3-D unfolding closure test results are compared to validate the 3-D unfolding
- Closure test is also done in other z bins

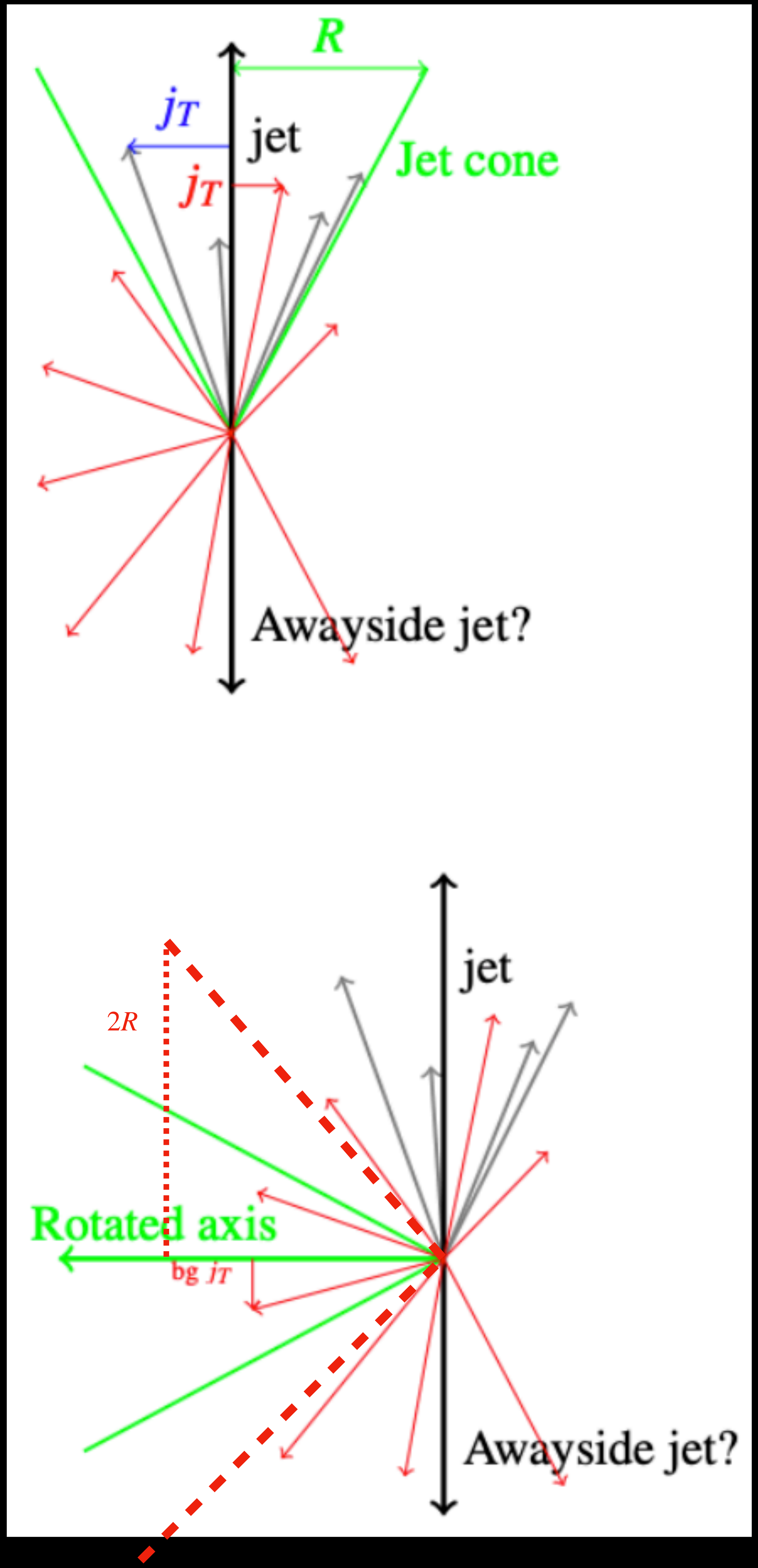
=

Data analysis

Background subtraction

Background estimation

- Perpendicular cone (Default)
  -Rotate the jet axis by 90° in a positive ϕ direction
  - If there are no other reconstructed jets around the rotated axis(Delta R<0.8), calculate j_{T}, z w.r.t the rotated axis
- j_{T}, z calculated with a perpendicular cone method was unfolded separately
- Used random background method for systematic check

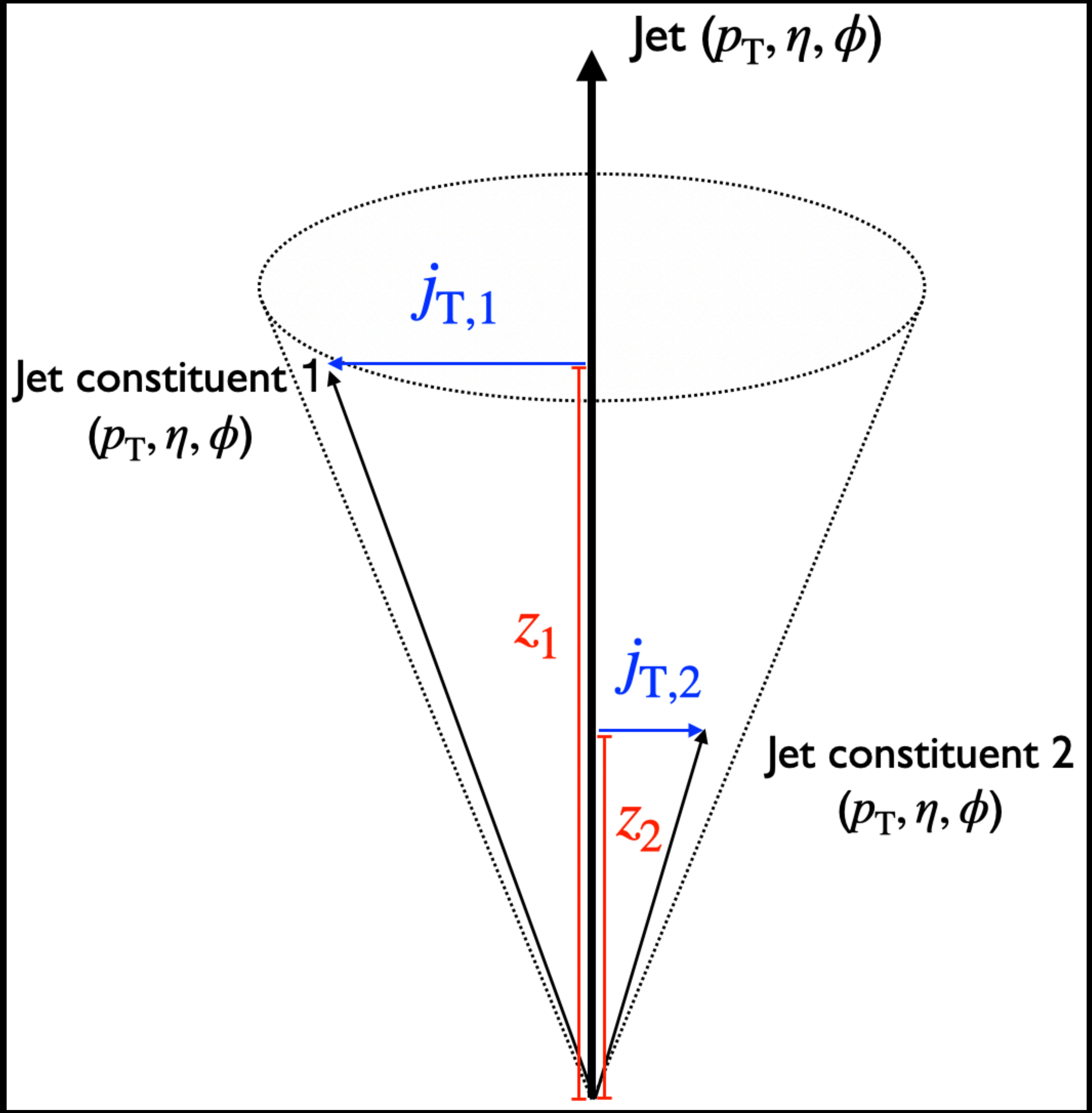


ALICE

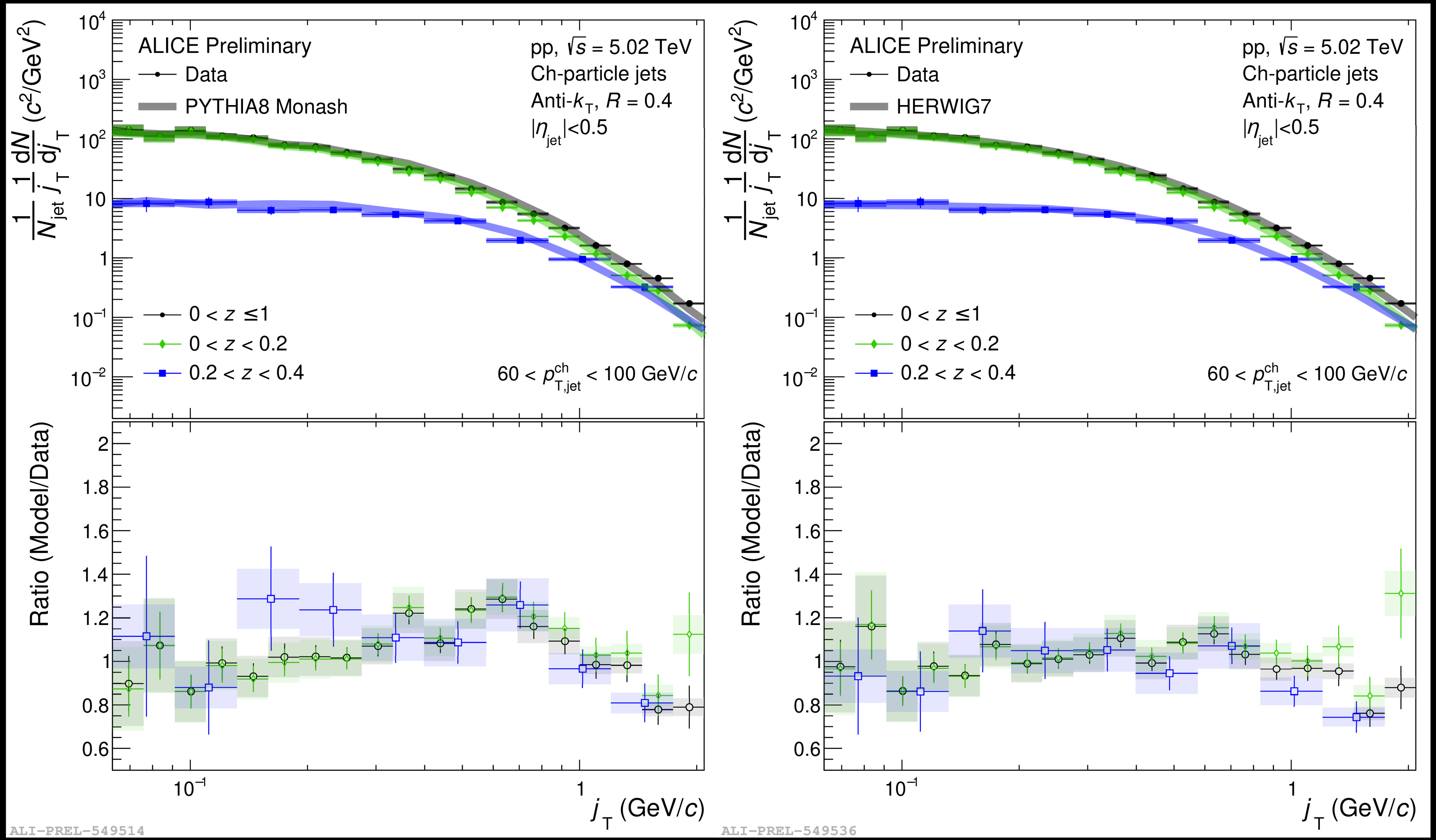
Systematic study

Systematic sources

- Systematic items
  - Unfolding
    - The number of iterations
    - Jet p_{T} threshold
    - Model dependence (jet angularity (g) difference)
    - Model dependence (MC generator for unfolding)
    - Tracking efficiency
  - Background subtraction method
- Systematic studies are done without bg subtraction



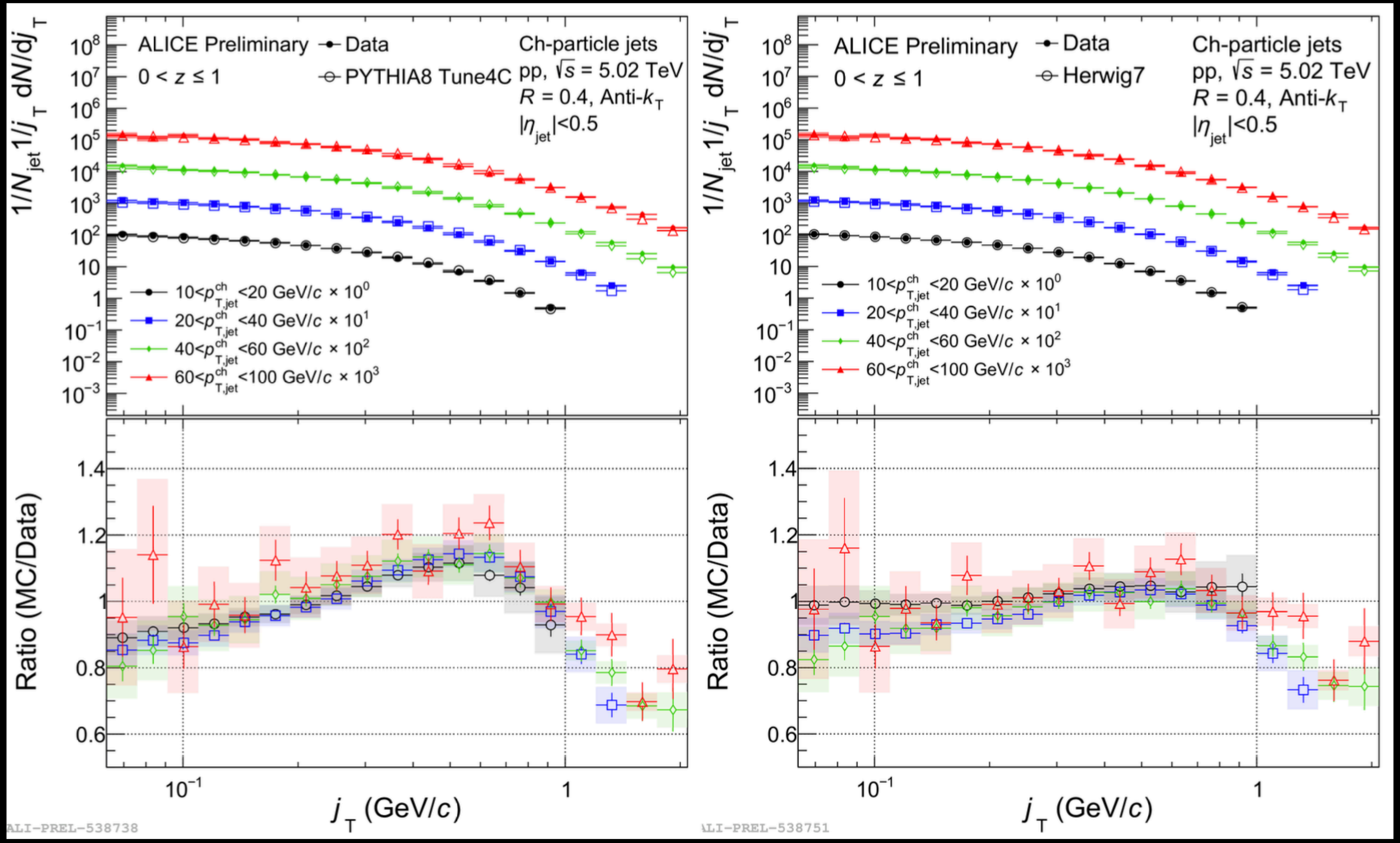
Results & model comparison



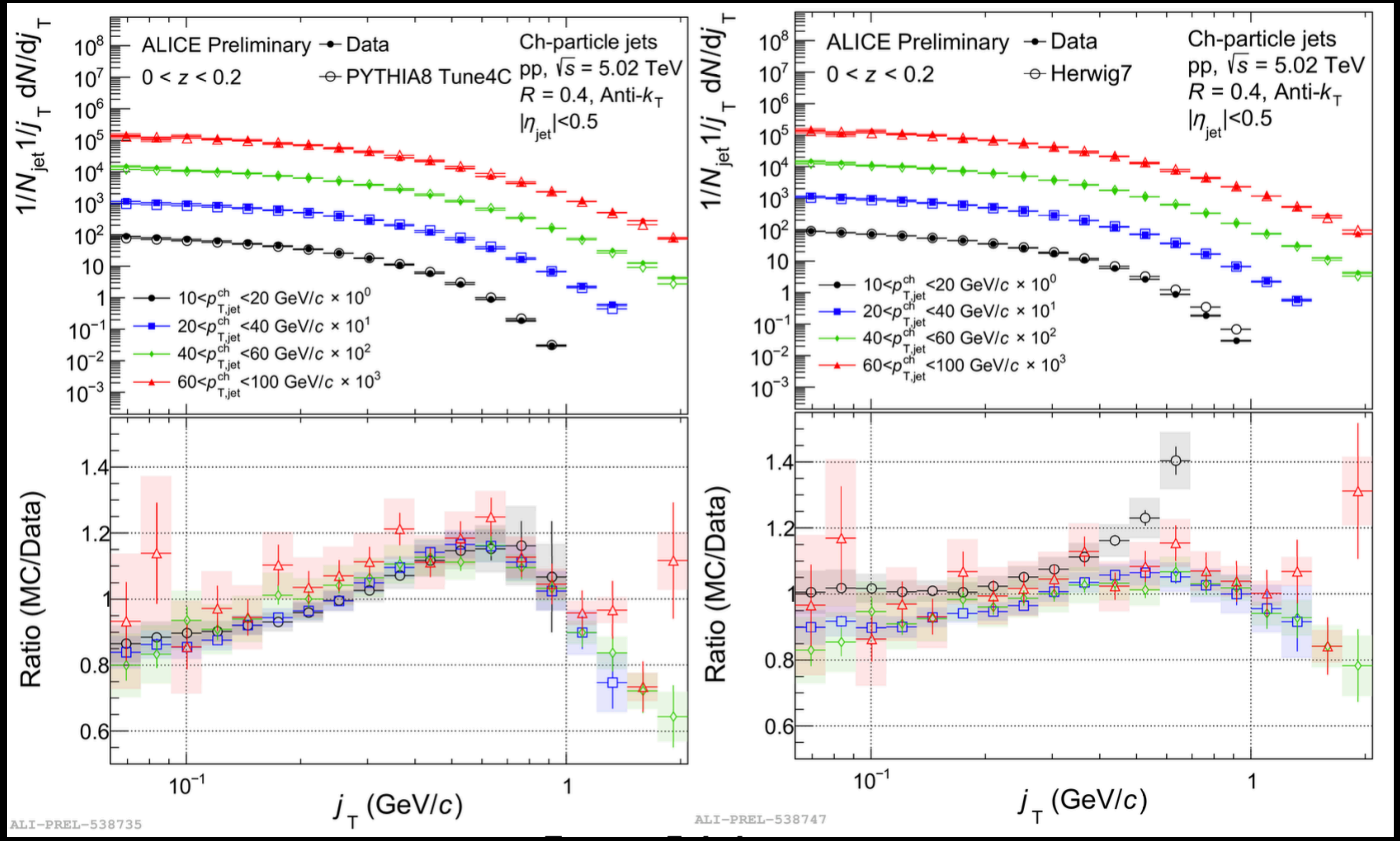
$60 < p_{T,jet} < 100$ GeV/c

- The j_T distributions for different $p_{T,jet}$ compared with PYTHIA8 Monash and HERWIG 7
- j_T distributions widen with increasing z
- Herwig underestimate the high z region and overestimate the low z, high j_T region
- Descriptions of models are different in the different kinematic ranges

Results & model comparison

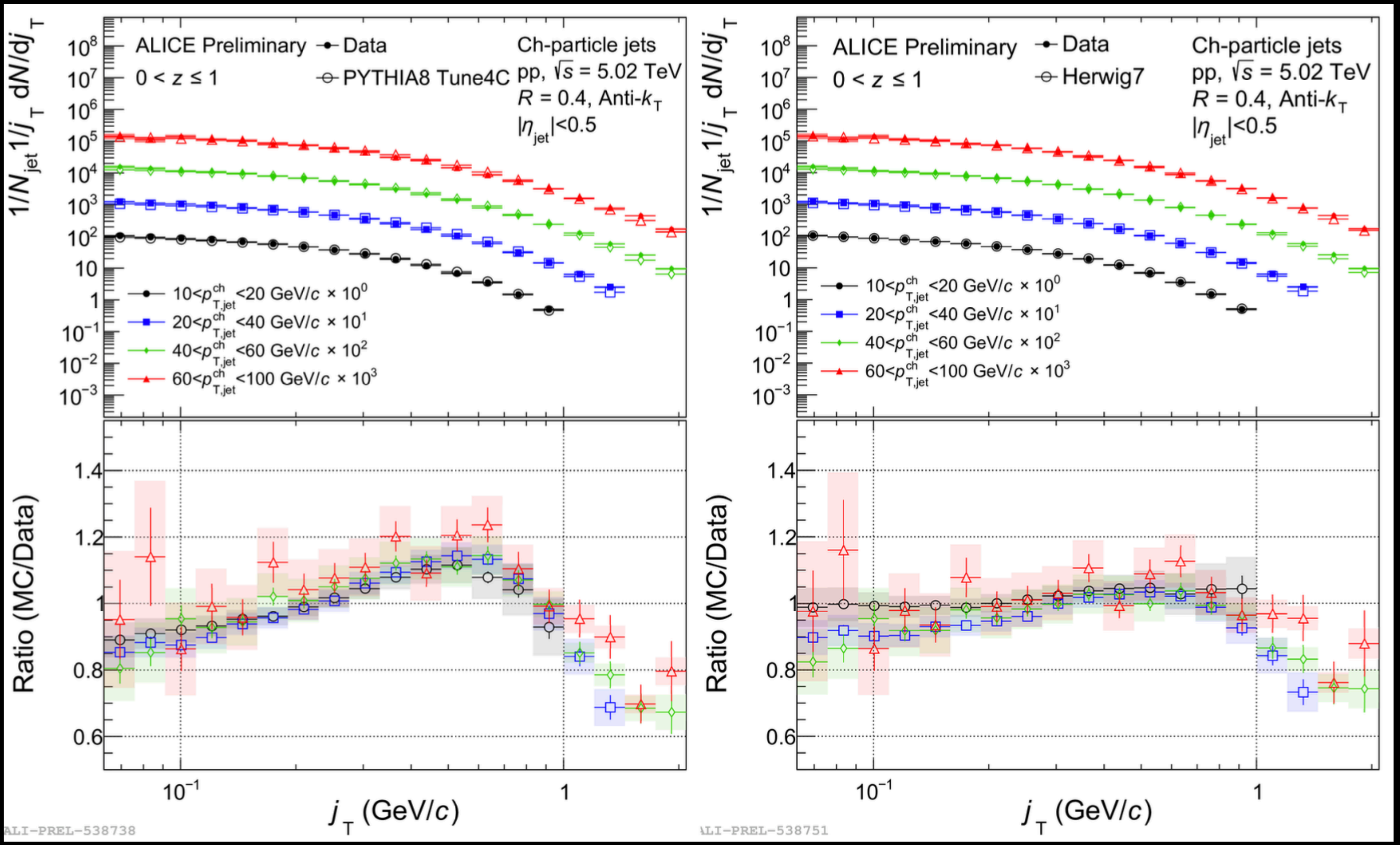


Inclusive z

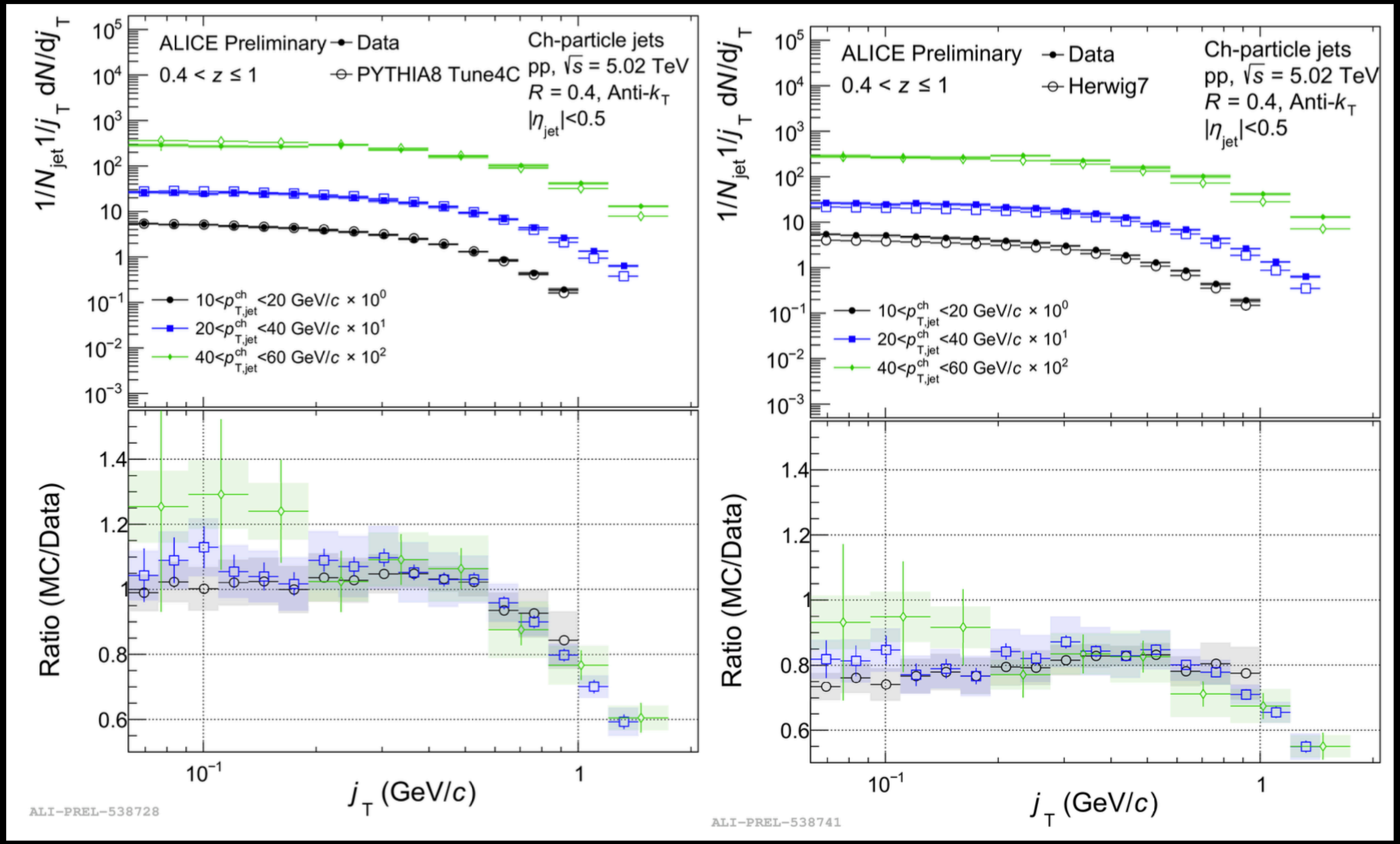


Low z

Results & model comparison



Mid z



High z